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# Hydraulic characterization of a highly anthropized coastal aquifer subject to tidal fluctuations

P. Fischer<sup>1</sup>, A. Jardani<sup>1</sup>, M. Krimissa<sup>2</sup>, C. Couegnas<sup>2</sup>

(1) Normandie Univ, UNIROUEN, UNICAEN, CNRS, M2C, GeoCNN Consortium, 76000 Rouen, France

(2) Electricité de France, EDF R&D, Laboratoire National d'Hydraulique et d'Environnement, 78401 Chatou, France

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**Corresponding author:** P. Fischer

**E-mail :**

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Tide, Coastal aquifer, Hydraulic barrier, Inverse modeling, France

## 1 **Abstract**

2 The hydraulic characterization of a highly anthropized coastal aquifer in France is presented.  
3 The current industrial operations of the study site prevent the use of standard ‘active’  
4 hydrogeological investigation methods (pumping, slug tests). However, the studied field is  
5 bordered on its north-western side by a channel directly connected to the sea, which allows for  
6 characterization of the hydraulic properties of the aquifer from its natural responses to the  
7 channel’s tidal signal. Piezometers (37) were monitored, from which oscillatory water-level  
8 responses (amplitude and phase-offset) to the tidal signal were extracted through linear  
9 regression and fast Fourier transform. A two-dimensional (2D) numerical model in the  
10 frequency domain was built to simulate the oscillations. The anthropic buried walls and barriers  
11 existing at the site are represented as 1D elements in a 2D model representing the properties of  
12 the aquifer. A deterministic inversion process optimizes the spatial distribution of aquifer  
13 properties and anthropic-structure properties in the model, in order to minimize the differences  
14 between the responses simulated with the model and those measured in the field. The results of  
15 the characterization on this complex study case (flows highly constrained by hydraulic barriers  
16 or buildings, and the impossibility to perform pumping tests) generate simulations able to  
17 reproduce the observed responses. The property and simulation maps generated make it  
18 possible to take into account the impact of the anthropic structures on the groundwater flows  
19 and to localize the parts of the hydraulic barriers where most exchanges between the channel  
20 and the aquifer occur.

## 21 **1. Introduction**

22 Hydraulic tomography techniques aim to determine the spatial distribution of hydraulic  
23 properties (conductivity and storage) of an aquifer by analyzing the punctual piezometric  
24 fluctuations due to an hydraulic solicitation of the groundwater (Carrera and Neuman 1986 ; de  
25 Marsily et al. 1995 ; Yeh and Lee 2007). Commonly, in an hydraulic tomography investigation,  
26 the hydraulic data are generated through cross-hole injections or extractions of groundwater  
27 while measuring the hydraulic head in piezometers (Cardiff et al. 2009 ; Illman et al. 2009 ;  
28 Fischer et al. 2017). Generally, the interpretation of the hydraulic data is completed by an  
29 inversion algorithm in which the hydraulic diffusion equation is numerically solved until  
30 iteratively finding a model of hydraulic properties able to match the piezometric data. The  
31 accuracy of the retrieved model depends on the nature of the inversion algorithm (stochastic  
32 and deterministic), and the amount and the localization of the measurement points on the field.  
33 However, the applicability of this strategy is limited to the characterization of productive  
34 aquifers, and when the observation and pumping wells are close enough to record a significant  
35 hydraulic variation.

36 The practice of pumping tests on industrial sites is a complex and supervised operation that  
37 requires the agreement of the public authorities. For this reason, the ability to perform pumping  
38 tests in the industrial area studied in this work is very limited. Another particular difficulty of  
39 this area is the necessity to take into account the walls and barriers that constrain the  
40 groundwater flow in the soil. The characterization of these structures is essential as they modify  
41 the groundwater flow paths, but also because they are often built to limit risks of contamination.  
42 The localization of potential leakages in such natural or anthropic barriers has been studied with  
43 different types of solicitation signals by several researchers (among them Vilarrasa et al. 2011  
44 ; Bolève et al. 2011 ; Sun et al. 2015). Alcolea et al. (2007) already took into account

45 heterogeneity due to anthropic structures in a zoned model of properties in order to constrain  
46 the preferential flow paths in the aquifer.

47 In the industrial study case reported here, the use of natural forces affecting the groundwater  
48 level, such as natural hydraulic level variations (D’Oria and Zanini 2019) or tidal variations  
49 induced by the lunar and solar forces (Rhoads and Robinson 1979), can be an interesting  
50 alternative when the use of active methods is limited. In particular, as this study site is situated  
51 along a channel directly connected to the sea, studying the groundwater responses to the natural  
52 tide appears to be the most appropriate option to derive the hydraulic properties of the aquifer  
53 and the barriers. In fact, the analysis of tidal oscillations provides a large-scale characterization  
54 of aquifers, including the hydraulic impact of some anthropogenic structures, such as the  
55 hydraulic barriers along the boundaries to the tidal source. This approach can be called  
56 ‘passive’, in comparison the ‘active’ approaches that require a human intervention to solicit  
57 water-table changes with oscillating signals (Bouwer and Rice 1976 ; Brauchler et al. 2010 ;  
58 Gultinan and Becker 2015). In the hydroscience literature, many studies have been devoted to  
59 the identification of hydraulic properties by exploiting the tide component in piezometric  
60 fluctuations. Among them Rhoads and Robinson (1979) used different periodic water-level  
61 variations (through ocean, earth and barometric tide signals) measured in three wells during  
62 two months to estimate various aquifer parameters (including specific storage and porosity)  
63 from analytical solutions. However the accuracy of their estimates was limited by a possible  
64 leakage effect in the aquifer, considered as confined. More recently, Wang et al. (2018)  
65 extended the analytical solutions to the responses to earth tides in order to estimate the  
66 transmissivity, storativity and specific leakage in leaky aquifers. In the cases of a coastal or an  
67 island aquifer, the oceanic tidal forces become particularly interesting. Thus, Tefry and Bekele  
68 (2004) and Wen et al. (2018) used the responses of island aquifers to the oceanic tides to  
69 estimate their heterogeneous properties. Alcolea et al. (2007) associated sea tides and injection

70 wells to reconstruct the distributions of transmissivity and storativity in a coastal area. The  
71 properties of riverine aquifers can also be assessed through their responses to tidal signals when  
72 the river is large enough to permit a propagation of the oceanic tides, as shown for example in  
73 Jardani et al. (2012). In that study, the authors inverted the tidal responses of an alluvial aquifer  
74 to a river connected to a sea to estimate its distributions of transmissivity and vertical leakage.  
75 These oscillatory signals can be modeled in a frequency domain, instead of a time domain  
76 (Black and Kipp 1981; Black et al. 1987; Fischer et al. 2018a), which reduces the computation  
77 time of the inverse problem. This partly explains why oscillatory signals have become a topic  
78 of particular interest in hydraulic tomography (Cardiff et al. 2013 ; Zhou et al. 2016 ; Fischer  
79 et al. 2018b).

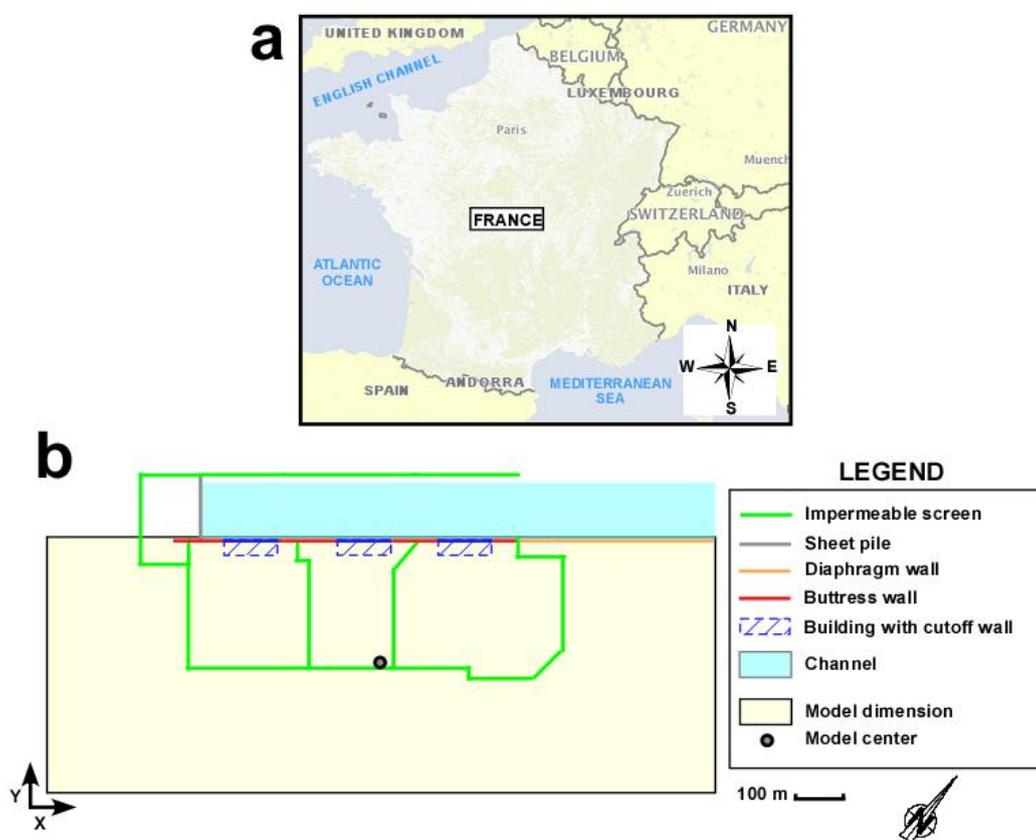
80 This study proposes a faster analysis of the hydraulic responses to the sea tidal fluctuation in  
81 the coastal aquifer by reformulating the transient mode of the inverse problem in a frequency  
82 domain. This work presents a new modeling method that permits one to simultaneously  
83 characterize the distributions of transmissivity and storativity in the aquifer and also localize  
84 potential leakages in hydraulic barriers by exploiting the natural sea tidal forces. This case study  
85 includes the anthropic structures and barriers in the inversion process in order to better simulate  
86 their impact on the complex flows on this site and to identify localizations, in these structures,  
87 where water exchanges between the aquifer and the channel are the most important. The paper  
88 first presents the study area, the dataset of measured hydraulic levels and the data processing  
89 that permits extraction of the tidal responses from the piezometric variations. Then the  
90 numerical model is presented, along with the inversion process that allows for a reconstruction  
91 of the properties in the model in order to reproduce the measured responses. Finally the results  
92 of the model are discussed in terms of reproduction of the responses and reconstruction of the  
93 distributions of transmissivity and storativity over the study area.

## 95 2. Site and data presentation

### 96 2.1. Study site

97 The study area is part of a highly anthropized industrial site located on the coast of France, half  
 98 a kilometer away from the sea. The site is connected to the sea through a channel of 10 to 15 m  
 99 depth. The study site involves an area of  $1,300 \times 500 \text{ m}^2$  along this channel, presented in Figure  
 100 1.

101



102

103 Figure 1: **a** Location of France. The study site is situated on the coast of France (the exact  
 104 location of the site is not indicated due to the confidentiality requirements of the study). **b**  
 105 Schematic top-down view of the site showing the location of the different anthropogenic  
 106 structures, the channel and the area of interest for the hydraulic characterization.

107

108 This area is highly anthropized and its surface is almost totally concreted over (buildings or  
109 roads). Its subsurface is a 30-m thick heterogeneous aquifer, lying on impermeable clays, and  
110 composed of different layers of sands separated by discontinuous lenses of silts. The channel  
111 and existing anthropogenic structures in this field are installed in the upper part of this aquifer,  
112 in a sandy unit, partially connected to the bottom part of the aquifer. The groundwater in this  
113 aquifer is confined by the compaction of the surface soil on the study field, due to the  
114 anthropization of the whole site.

115 The groundwater flows in this area are constrained by buried 10–15 m deep sheet piles, barriers  
116 and walls (Figure 1) that have a thickness of 50 cm. The channel and the barriers are cutting  
117 through the confining surface soil and influence the groundwater flows. Three buildings,  
118 installed up to 16 m underground, located alongside the channel could also have an impact on  
119 the flows.

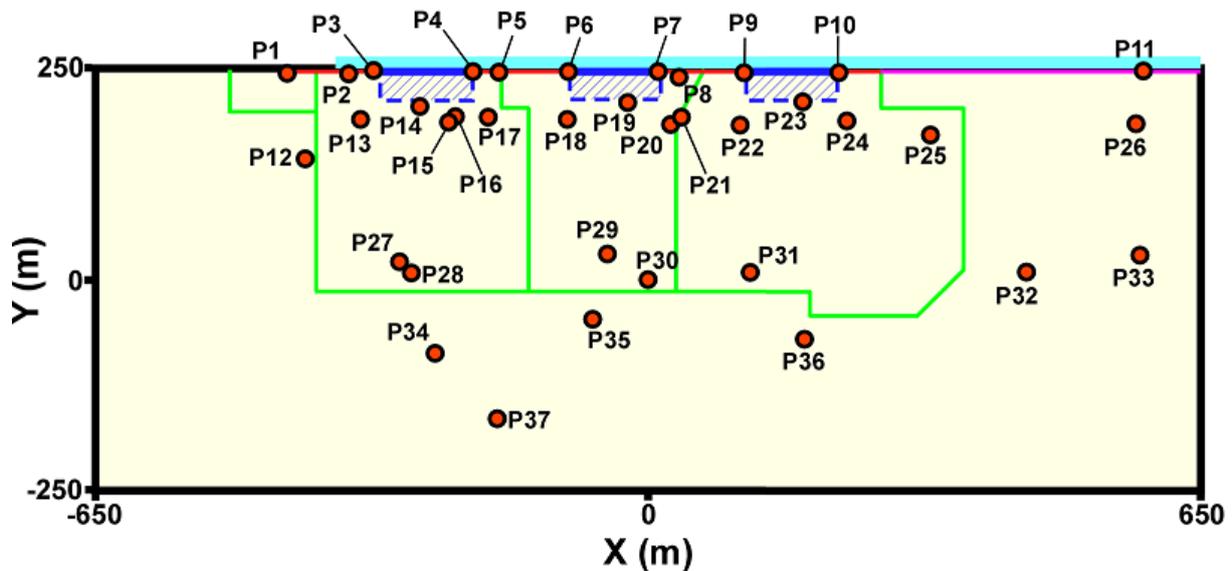
120 Therefore two strategies of two-dimensional (2D) modeling will be tested in this study, one that  
121 takes into account these buildings as constraints and the other not. It was decided to use 2D  
122 models instead of 3D ones because the dataset, composed of piezometric measures, is  
123 integrative and does not allow for a 3D characterization. Furthermore, 2D models are faster to  
124 solve and, therefore, allow for a higher resolution of property spatial distributions in the  
125 inversion processes. As, in this case, the groundwater flows in the investigated section (10 to  
126 15 m depth) are mostly horizontal and perturbed by structures modifying locally this spatial  
127 distribution in the property fields, it is believed that modeling in a 2D top-down view is the best  
128 compromise of accuracy and time consumption.

## 129 **2.2. Piezometric responses to the tidal signal**

130 The piezometric responses in the aquifer are measured continuously and automatically each 15  
131 minutes by probes in 37 piezometers distributed over the study area (Figure 2). These

132 piezometers were drilled to a depth of 10m and are screened from 5 m to 10 m depth. The  
 133 hydraulic level in the channel is also measured automatically each hour by a probe. All these  
 134 recorded data are saved in a private repository, property of Electricité de France (EDF).

135



136

137 Figure 2: Location and designation of the 37 piezometers measuring continuously the  
 138 groundwater level at the studied site.

139

140 As it is an industrial site in operation, it is too difficult to perform any pumping tests in the area.  
 141 In this case, the use of the tidal oscillation as a solicitation signal is the most appropriate option  
 142 to derive the hydraulic properties of the aquifer and the barriers. A piezometric dataset covering  
 143 a period of four days of measurements in November 2016 was selected. During this period the  
 144 rainfall recharge was particularly low (six consecutive days without rain), which meant that the  
 145 groundwater responses to the tidal signal in the piezometric measurements could be more  
 146 precise.

147

148

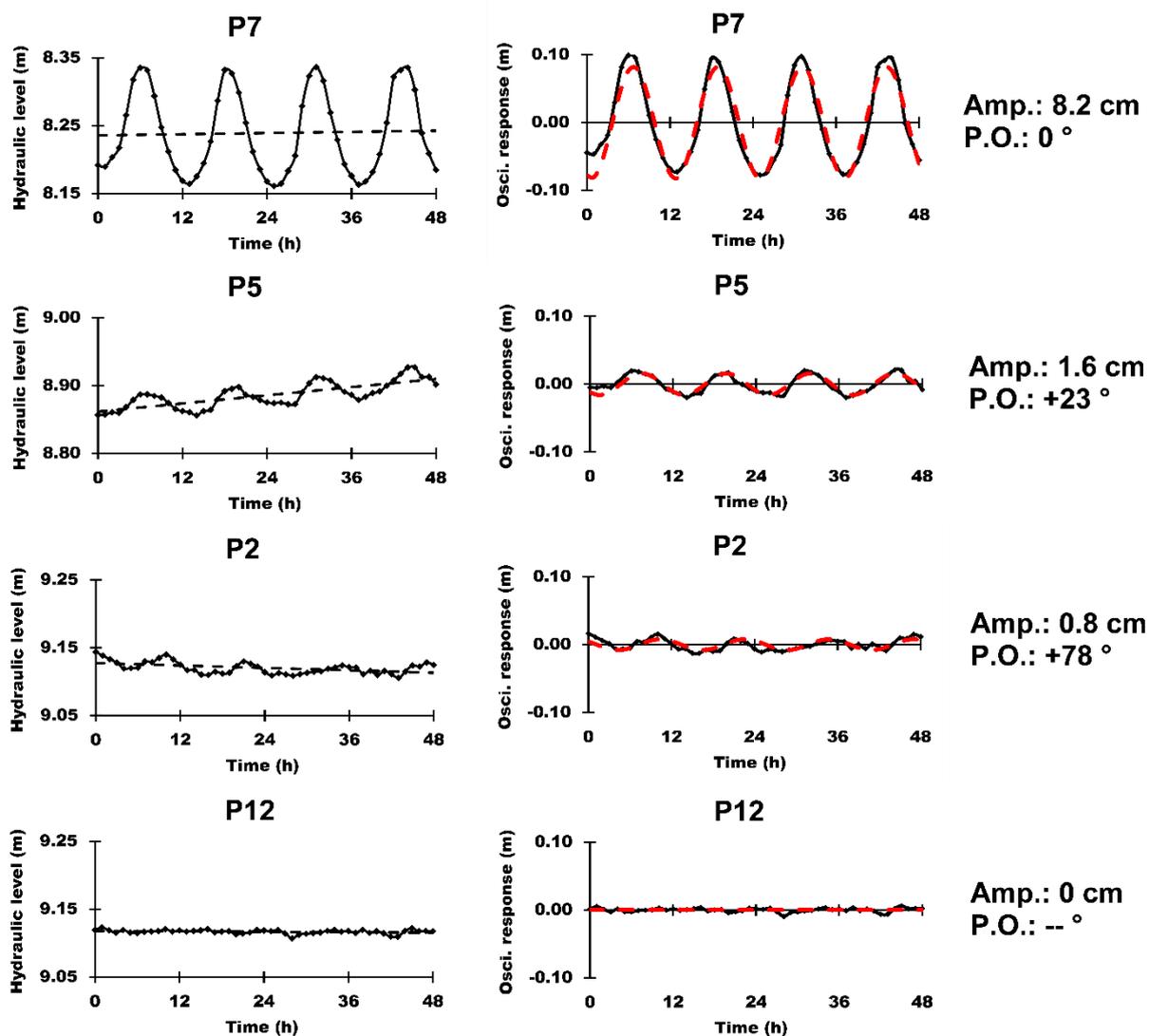
149 **2.3. Data processing**

150 It is noted that the piezometric level measurements in the field could be approximated as the  
 151 sum of a linear response and an oscillatory response (see Figure 3):

152 
$$h(x,y,t) \approx h_{osc.}(x,y,t) + h_{lin.}(x,y,t) \quad (1)$$

153 with  $h$  the hydraulic level response over space and time in m,  $h_{osc.}$  the oscillatory part of the  
 154 response in m, and  $h_{lin.}$  the linear part of the response in m, which represents an approximation  
 155 of the non-tidal temporal trend in groundwater elevations.

156



157

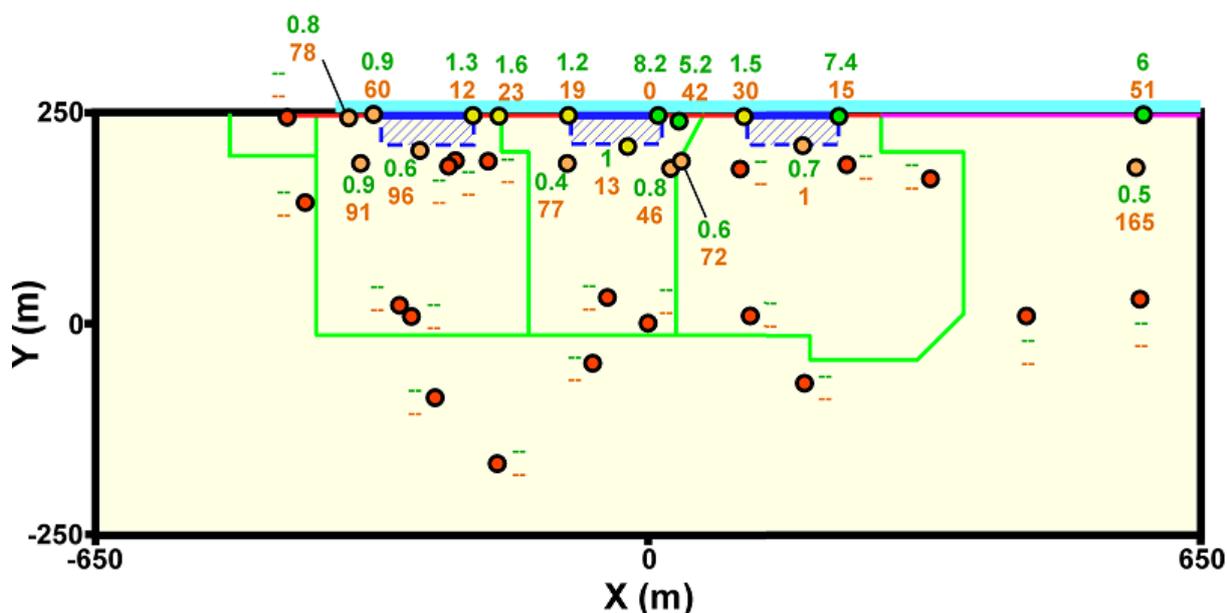
158 Figure 3: Example of data processing for four different piezometer (P7, P5, P2, P12) responses.  
 159 In the left panel, a linear component (dotted lines), found through linear regression, is subtracted  
 160 from the measured hydraulic level in order to assess only the oscillatory part of the response  
 161 (Eq. 1). Then, in the right panel, a fast Fourier transform (FFT) is performed (red dashed lines)  
 162 on the oscillatory part (black lines) to interpret the response of each piezometer in terms of  
 163 amplitude (Amp.) and phase-offset (P.O.). The phase-offset responses are calculated relative to  
 164 the signal of P7, the piezometer closest to the channel. P.O.: '--' designates a negligible  
 165 oscillatory response (< 5 mm amplitude).

166

167 As the aim is to study specifically the oscillatory responses to the tidal signal, one can extract  
 168 these oscillatory responses from the measurements by subtracting the linear responses, obtained  
 169 through a linear regression. Then, one can assess the amplitude and phase-offset values of the  
 170 isolated oscillatory responses by performing a fast Fourier transform (FFT) on them, as the  
 171 period of the sea tidal signal (12.2 hours) at this location is known from the French Naval  
 172 Hydrographic and Oceanographic Service data. Examples of the data processing undertaken on  
 173 four different piezometer measurements are presented in Figure 3.

174 Once the amplitude and phase-offset responses to the tidal signal for each piezometer have been  
 175 extracted, it is possible to create a map of spatial intensity of these responses (Figure 4).

176



177

178 Figure 4: Amplitude and phase-offset responses interpreted from the signals of each piezometer  
179 on the site. The amplitude responses in green are in cm, the phase-offset responses in orange  
180 are in degrees ( $^{\circ}$ ). Green circles designate responses with amplitudes higher than 2 cm, yellow  
181 circles designate amplitudes between 1 and 2 cm, and orange circles designate amplitudes  
182 between 0.5 and 1 cm. The red circles with ‘--’ designate responses with a negligible amplitude  
183 ( $< 5$  mm).

184

185 From this map, it appears that piezometers closer to the channel show more intensive oscillatory  
186 responses. This shows that the oscillatory responses measured from the piezometers are indeed  
187 responses to the tidal signal of the channel. In contrast, piezometers that are located more than  
188 125 m away from the channel do not respond to its signal, which has attenuated in the aquifer.  
189 This means that the tidal signal will only permit characterization of a band of approximately  
190 125 m alongside the channel.

191 The intensities and the phase lags of the responses directly along the channel are very variable.  
192 This effect can be attributed to the hydraulic barriers along the channel, and more specifically  
193 to a spatial variation of the efficiency of these barriers.

194 It also appears from this map that the amplitude response decreasing when moving away from  
195 the channel is generally associated to an increasing phase-offset response. This observation is  
196 in agreement with several other works on oscillatory responses (Renner and Messar 2006 ;  
197 Rabinovich et al. 2015 ; Zhou et al. 2016 ; Fischer et al. 2018a). Two boreholes, P19 and P23,  
198 present a low amplitude associated to a low phase offset. This could be attributed to a cycle  
199 delay in the phase. This hypothesis can be verified in the following modeling simulations.

200 The next step of this study aims to interpret the distribution of amplitude and phase-offset  
201 responses over the field in terms of distribution of transmissivity and storativity. This can be  
202 performed with an inversion process in a numerical model.

203

### 204 3. Modeling strategy

#### 205 3.1. Forward problem and model parameterization

206 This study aims to reproduce the measured amplitude and phase-offsets in the oscillatory  
 207 responses in a 2D model, in order to map the distribution of the transmissivity and storativity  
 208 properties of the aquifer and the anthropic structures in the field.

209 In order to reduce the computation time when solving the model, the numerical modeling is  
 210 performed in a frequency domain. In fact, the oscillatory responses can be rewritten in complex  
 211 form as follows:

$$212 \quad h_{\text{osc.}}(x, y, t) = A(x, y) \cos\left(\omega t - \Phi(x, y) \frac{\pi}{180}\right) = \text{Re}\left(H_{\omega}(x, y) e^{i\omega t}\right) \quad (2)$$

213 with  $A$  the amplitude of the signal in m,  $\Phi$  the phase offset of the signal in  $^{\circ}$ ,  $\omega$  the angular  
 214 frequency of the signal in  $\text{rad}\cdot\text{s}^{-1}$ ,  $H_{\omega}$  the complex variable carrying the oscillatory responses  
 215 in the frequency domain,  $\text{Re}$  the real part of a complex number and  $i$  the imaginary unit.

216 The 2D model is built with the software COMSOL Multiphysics. The dimensions of the model  
 217 are presented in Figure 2, with the channel considered as a linear boundary condition. This  
 218 model is enclosed in a buffer zone of dimensions  $3000 \times 2000 \text{ m}^2$  and associated with uniform  
 219 regional aquifer properties, which permits limitation of the impact of the other external  
 220 boundary conditions. The aquifer properties are represented in 2D in the model, while the  
 221 anthropic structures' properties are represented in 1D along lines representing the walls and  
 222 barriers presented in Figure 1.

223 The groundwater flows are simulated using the continuity equation in the frequency form,  
 224 considering Darcy's law and the following initial and boundary conditions:

$$\begin{cases} i\omega S(x,y)H_{\omega}(x,y)-\nabla(T(x,y)\nabla H_{\omega}(x,y))=0 & \text{in 2D} \\ i\omega S_{\text{barrier}}(x,y)H_{\omega}(x,y)-\nabla(T_{\text{barrier}}(x,y)\nabla H_{\omega}(x,y))=0 & \text{in 1D} \end{cases}$$

225 (3)

$$\text{with } H_{\omega,\text{init}}(x,y)=0 \quad \text{and} \quad \begin{cases} H_{\omega}(x,y)_{\text{channel}}=0.082 \\ H_{\omega}(x,y)_{\text{bound.}}=0 \end{cases}$$

226 with  $S$  the storativity (no unit),  $T$  the transmissivity in  $\text{m}^2.\text{s}^{-1}$ ,  $S_{\text{barrier}}$  and  $T_{\text{barrier}}$  being related  
 227 to the 1D barrier structures in the model.  $H_{\omega,\text{init}}$ ,  $H_{\omega}(x,y)_{\text{channel}}$ ,  $H_{\omega}(x,y)_{\text{bound.}}$  are the initial  
 228 and boundary conditions of the model. The value for the channel condition is chosen according  
 229 to the oscillation generated by the channel in the soil. As the barriers might have produced local  
 230 non-Darcian effects on the flows, and as Darcy flows are considered in the simulations, it is  
 231 more correct to refer to  $S_{\text{barrier}}$  and  $T_{\text{barrier}}$  as equivalent storativities and transmissivities  
 232 incorporating these non-Darcian effects. However, as the aim is to characterize these structures  
 233 and their relative efficiency in space rather than their exact values, equivalent properties are  
 234 sufficient.

235 The resolution of the model is performed with a finite element method, along a triangular mesh.

236 The amplitude and phase-offset spatial simulations can then be extracted following the  
 237 formulas:

$$\begin{cases} A(x,y)=\sqrt{(\text{Re}H_{\omega}(x,y))^2+(\text{Im}H_{\omega}(x,y))^2} \\ \Phi(x,y)=\frac{180}{\pi}\text{atan2}(-\text{Im}H_{\omega}(x,y),\text{Re}H_{\omega}(x,y)) \end{cases} \quad (4)$$

239  $\text{Im}$  represents the imaginary part of a complex number and  $\text{atan2}$  is the 2-argument arctangent  
 240 function. The spatial oscillatory responses in the time domain can be reconstructed using the  
 241 amplitudes and phase-offsets simulated in the frequency domain and the formula in Eq. 2.

242

### 243 3.2. Inverse problem

244 The distributions of the transmissivity and storativity properties in the model are reconstructed  
 245 through an inversion process. Therefore the property values distributed over a regular grid  
 246 composed of rectangular cells (aquifer) and over lines composed of regular segments  
 247 (structures) are stored in a vector  $\mathbf{p}$ . The deterministic optimization that consists of modifying  
 248 the values in  $\mathbf{p}$  in order to improve the reproduction of the measured responses with the model,  
 249 is then performed through an iterative process that aims at minimizing the following objective  
 250 function:

$$251 \quad \Psi = (\mathbf{d}_{\text{obs.}} - f(\mathbf{p}))^T \mathbf{C}_d^{-1} (\mathbf{d}_{\text{obs.}} - f(\mathbf{p})) + (\mathbf{p}_{\text{prior}} - \mathbf{p})^T \mathbf{C}_p^{-1} (\mathbf{p}_{\text{prior}} - \mathbf{p}) \quad (5)$$

252 with  $\mathbf{d}_{\text{obs.}}$  and  $f(\mathbf{p})$  the  $n$ -vectors containing respectively the measured and simulated  
 253 amplitude and phase offset responses,  $\mathbf{p}$  and  $\mathbf{p}_{\text{prior}}$  the  $m$ -vectors containing respectively the  
 254  $S$  and  $T$  distributions in the model and their *a priori* distributions, and  $\mathbf{C}_d$  and  $\mathbf{C}_p$  the  $n \times n$   
 255 and  $m \times m$  matrices of covariance on the set of responses and the property distribution,  
 256 respectively.

257 As the deterministic inversion is iterative, it is first necessary to initialize the values in  $\mathbf{p}$  with  
 258 reasonable property values. Then, at a given iteration step  $k$ , the property values in  $\mathbf{p}$  can be  
 259 optimized considering the values from the previous step with a linearization using a first-order  
 260 Taylor approximation:

$$261 \quad f(\mathbf{p}_{k+1}) \approx f(\mathbf{p}_k) + \mathbf{F}_k (\mathbf{p}_{k+1} - \mathbf{p}_k)$$

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

262 with  $\mathbf{p}_k$  and  $\mathbf{p}_{k+1}$  the property distribution at iterations  $k$  and  $k+1$ ,  $\mathbf{F}_k$  the  $n \times m$  Jacobian  
 263 matrix calculated at iteration  $k$  with a finite-difference method, and  $\Delta p$  the finite difference  
 264 step.

265 Then,  $\mathbf{p}_{k+1}$  is calculated as:

$$266 \quad \mathbf{p}_{k+1} = \mathbf{p}_k + \left( \mathbf{F}_k^T \mathbf{C}_d^{-1} \mathbf{F}_k + \mathbf{C}_p^{-1} \right)^{-1} \cdot \left( \mathbf{F}_k^T \mathbf{C}_d^{-1} (\mathbf{d}_{\text{obs.}} - f(\mathbf{p}_k)) + \mathbf{C}_p^{-1} (\mathbf{p}_{\text{prior}} - \mathbf{p}_k) \right) \quad (7)$$

267 Finally, once the objective function has been sufficiently minimized, the optimization iterations  
 268 are stopped. The uncertainties on the final property values in  $\mathbf{p}$  can be estimated as follows:

$$269 \quad \mathbf{p}_{\text{uncert.}}(i) = \sqrt{\mathbf{C}_{\text{p,post}}(i,i)} \quad (8)$$

where  $\mathbf{C}_{\text{p,post}} = \left( \mathbf{F}_{\text{post}}^T \mathbf{C}_d^{-1} \mathbf{F}_{\text{post}} + \mathbf{C}_p^{-1} \right)^{-1}$

270 with  $\mathbf{p}_{\text{uncert.}}$  the  $m$ -vector of standard deviations associated to the property values of the final  
 271 model,  $\mathbf{C}_{\text{p,post}}$  the  $m \times m$  matrix of posterior covariance on the property distribution, and  $\mathbf{F}_{\text{post}}$   
 272 the Jacobian matrix calculated during the last iteration.

### 273 3.3. Inversion parameters

274 The inversion algorithm is coded with MATLAB and performed using the  
 275 MATLAB/COMSOL connection to solve the forward model. The different values of inversion  
 276 parameters chosen for this study case are presented in Table 1.

277 The property values to be optimized in the model are distributed, for the aquifer, over a grid  
 278 composed of 2000 rectangular cells, and for the walls located along the channel, over a line  
 279 composed of 100 regular segments. All other buried structures existing as 1D lines in the model  
 280 are considered as a unique entity in the inversion, thus associated to uniform values of  
 281 equivalent properties. In this way, 4200 unknown transmissivities and storativities will be

282 considered in the inversion process. This resolution allows for sufficient liberty, in order to  
 283 reproduce the complexity of the field flows, while also keeping an acceptable duration of the  
 284 inversion process.

285 Table 1: Parameter values used for the inverse modeling.

Parameter	Value
Data uncertainty	$\pm 0.1$ cm on amplitude $\pm 10^\circ$ on phase-offset
Property distribution resolution	$100 \times 20$ cells distributed over $X \in [-450 ; 650]$ and $Y \in [125 ; 250]$
Property distribution variogram function	$\text{Var}(\text{distance}) = 0.1 \times \left[ 1 - \exp\left(-\frac{\text{distance}}{8}\right) \right]$
Buried walls (channel) property resolution	100 segments
Buried structures' property variance	$\sigma_{\text{str}}^2 = 10^{-1}$
Initial transmissivities	Aquifer: $3.10^{-6}$ m <sup>2</sup> /s; Structure: $10^{-9}$ m <sup>2</sup> /s ; Building: $10^{-7}$ m <sup>2</sup> /s
Initial storativities	Aquifer: $5.10^{-5}$ ; Structure: $10^{-2}$ ; Building: $10^{-3}$
Finite difference step	$10^{-5}$
Buffer zone	$T = 3.10^{-6}$ m <sup>2</sup> /s ; $S = 5.10^{-5}$

286

287 The vectors  $\mathbf{p}$  and  $\mathbf{p}_{\text{prior}}$  are built using the  $-\log_{10}$  values of transmissivity and storativity  
 288 presented in Table 1. The initial property values are also used as a priori values for the inversion  
 289 in  $\mathbf{p}_{\text{prior}}$ . These initial values are chosen according to values presented for regional studies of  
 290 this aquifer, while the structure and building equivalent properties are set voluntarily to low  $T$   
 291 and high  $S$  in order to lower flows through these parts of the model.

292 The covariance matrix  $\mathbf{C}_d$  is built as a diagonal matrix. Its diagonal entries are the data  
 293 uncertainty values (Table 1) associated, respectively, to the amplitude responses and the phase-  
 294 offset responses in  $\mathbf{d}$  and  $\mathbf{d}_{\text{obs.}}$ . The covariance matrix  $\mathbf{C}_p$  is built as a variogram matrix for

295 its parts associated to the aquifer properties and as a diagonal matrix for the parts associated to  
296 the structures' properties. Its variogram part is calculated with the variogram function (Table  
297 1), by taking into account the distances between each cell of the property grid. This variogram  
298 remains voluntarily permissive, in order to allow for some spatial variations while also avoiding  
299 discontinuities in the distribution. Its diagonal part is built with the buried structures' property  
300 variance value (Table 1).

301 Two inversions were performed: one taking into account the three buildings along the channel  
302 by considering specific ('building') initial property values in their zones, and one not taking  
303 them into account by considering the 'aquifer' initial properties in their zones. An impact of the  
304 building structures on the groundwater flows is in fact not certain, therefore it is interesting to  
305 perform these two inversions.

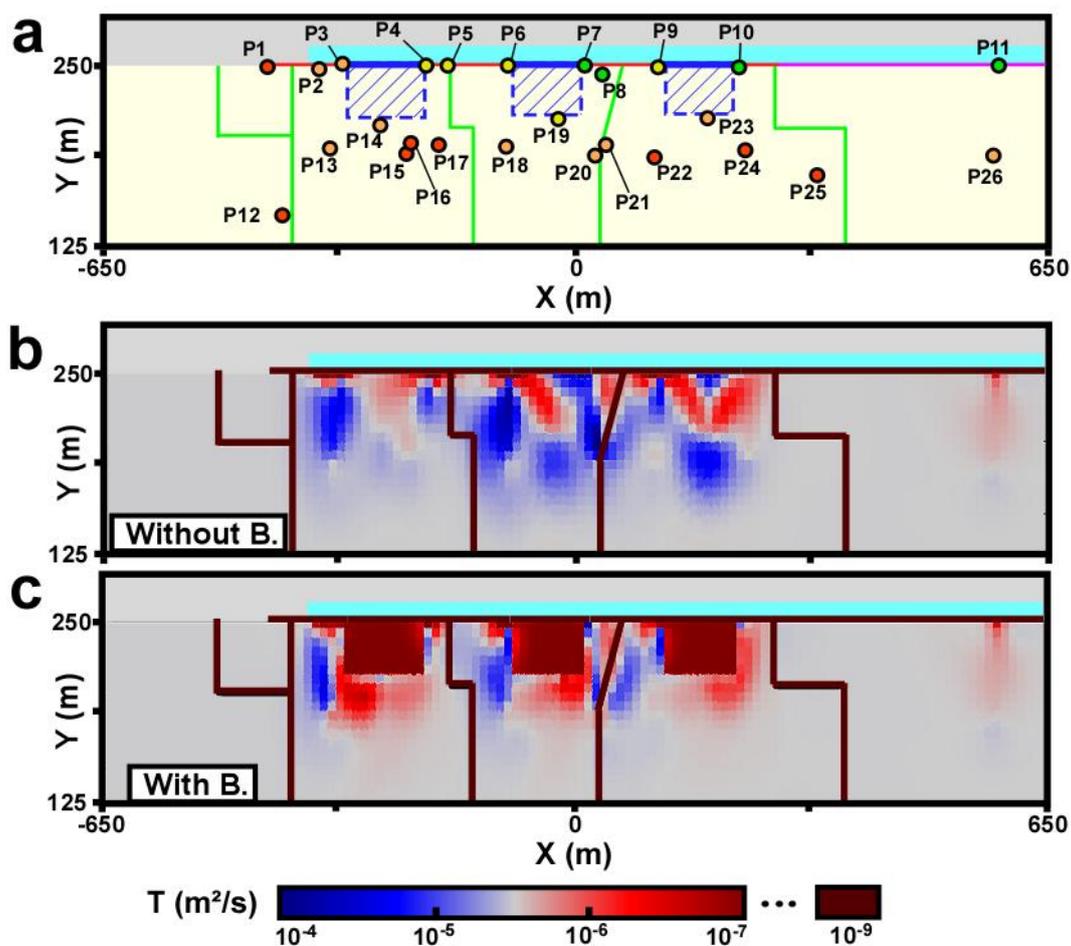
## 306 **4. Results and discussion**

### 307 **4.1. Comparing models with or without integrating buildings**

308 The transmissivity and storativity maps derived from the inversion processes are presented  
309 respectively in Figure 5 and Figure 6. The reproduction of the 37 measured responses with these  
310 models is presented in Figure 7.

311 Note that the distributions of the properties in the aquifer are very heterogeneous and in a wide  
312 range of values (from  $10^{-4}$  m<sup>2</sup>/s to  $10^{-6}$  m<sup>2</sup>/s for the transmissivities and from  $10^{-3}$  to  $10^{-6}$  for the  
313 storativities).

314



315

316 Figure 5: **a** The location of the piezometers in the (zoomed-in) zone near the channel. Maps of  
 317 inverted transmissivities ( $T$ ) for the inversions **b** taking into account the buildings (With B.)  
 318 and **c** not taking into account the buildings (Without B.).

319

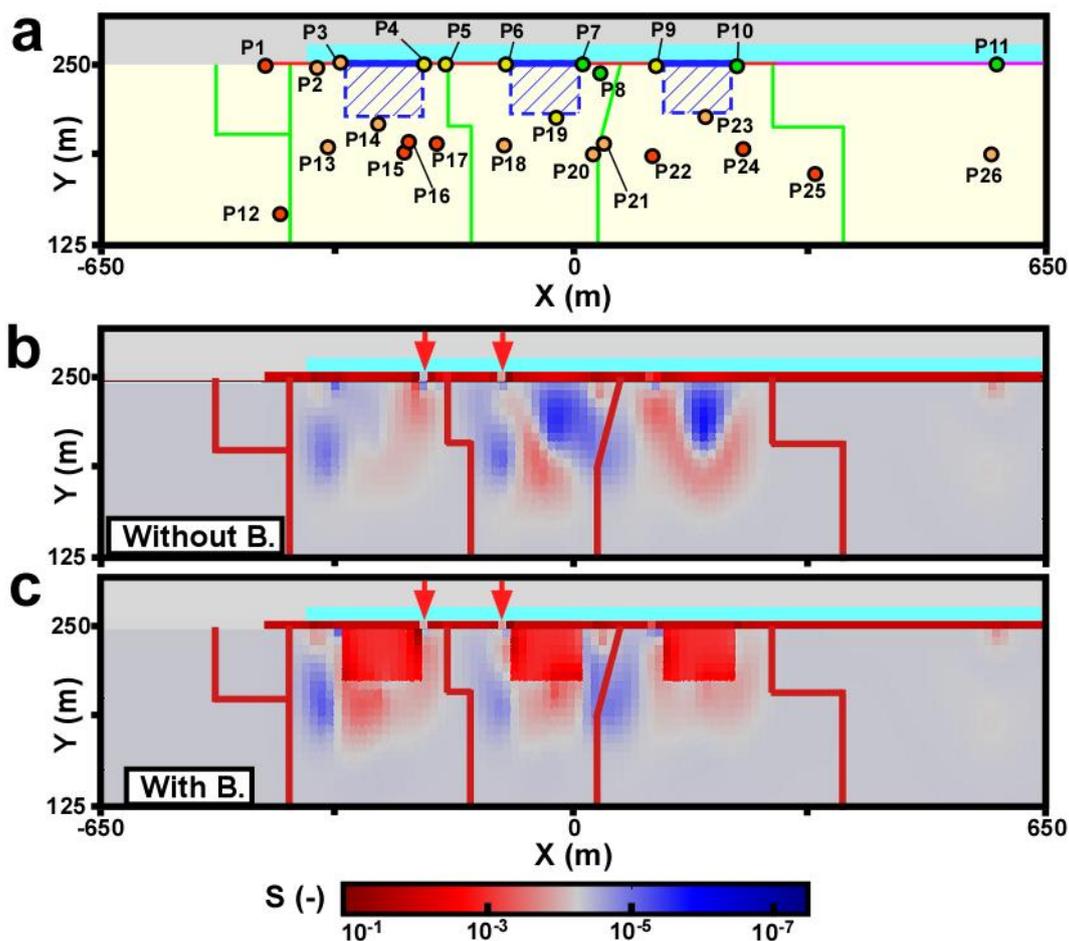
320 In the inversion ‘without buildings’ it is observed that a low transmissivity has been attributed  
 321 to the area of the buildings and that the two transmissivity maps (with and without buildings)  
 322 present different distributions in the areas surrounding the buildings (especially on their side  
 323 opposite the channel). Therefore, concerning the transmissivity distribution, taking into account  
 324 the buildings as *a priori* knowledge, does significantly modify the result of the inversion.

325 Concerning the storativity distribution, it is noted that neither the ‘without building’ distribution  
 326 increases the storativity values in the building areas, nor the areas surrounding the buildings is  
 327 different between the results of the inversions ‘with buildings’ or ‘without buildings’. Then,

328 contrarily to the transmissivity distribution, taking into account the buildings as *a priori*  
329 knowledge does not seem to impact significantly the inversion of the storativity distribution.  
330 This suggests that the flows in the aquifer in the buildings area are mostly driven by the  
331 transmissivity.

332 It is also interesting to observe that the distribution of the blue zones (high transmissivity, low  
333 storativity) and the red zones (low transmissivity, high storativity) in Figures 5 and 6 is much  
334 more coherent in the results of the inversion 'with buildings'. The distributions of the blue and  
335 red zones in the transmissivity and storativity maps inverted in this case are, indeed, much more  
336 similar than in the results of the inversion 'without buildings'.

337



338

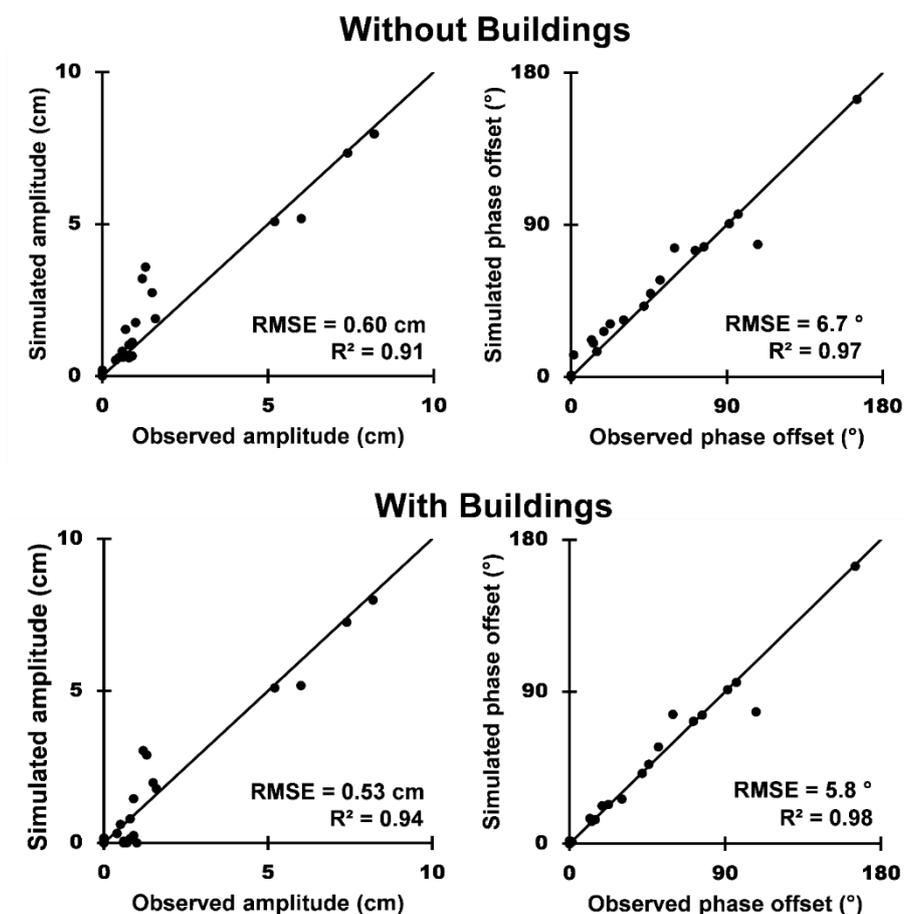
339 Figure 6: **a** The location of the piezometers in the (zoomed-in) zone near the channel. Maps of  
 340 inverted storativities ( $S$ ) for the inversions **b** taking into account the buildings (With B.) and **c**  
 341 not taking into account the buildings (Without B.). The red arrows designate the less efficient  
 342 segments of the anthropic structures in the model.

343

344 Concerning the distribution of the equivalent properties along the different anthropic structures,  
 345 the optimization process modified the storativity values more than the transmissivity values. In  
 346 fact, the equivalent storativity values in the results range from  $10^{-1}$  to  $10^{-4}$ , while the equivalent  
 347 transmissivity values remain close to the initial value  $10^{-9}$  m<sup>2</sup>/s. The distribution of the  
 348 equivalent storativities along the walls in the model is therefore more relevant to localization  
 349 of the more and less efficient parts of the hydraulic barrier constructed along the channel. The  
 350 red arrows in Figure 6 show the localization of the relatively less efficient parts of the barriers

351 in the two inversion results. It was first observed that these localizations are exactly the same  
 352 in both results, which indicates again that the buildings' a priori information do not significantly  
 353 affect the inversion of the storativity distribution. The two relatively less efficient parts of the  
 354 hydraulic barriers are located at the junctions between buttress walls and cutoff walls, thus they  
 355 could be associated to the sealing between these walls.

356



357

358 Figure 7: Amplitudes and phase-offsets measured versus amplitudes and phase-offsets  
 359 simulated with the property distributions presented in Figures 5 and 6. Each graph is associated  
 360 to the values of  $R^2$  and root mean square error (RMSE) between the simulated and measured  
 361 data.

362

363 Globally the reproduction of the amplitude and phase offset responses is very similar with the  
 364 property maps inverted with or without the buildings. However, the model 'with buildings',

365 incorporating an *a priori* knowledge, provides a slightly better simulation of the measured  
366 responses.

367 The transmissivity distributions in these results (Figure 5) and the responses' reproduction  
368 (Figure 7) suggest that the local decrease of transmissivity induced by the buildings is necessary  
369 in the model to simulate its impact on the groundwater flows. Therefore, the rest of the article  
370 addresses essentially the model of the inversion 'with buildings', which seems to provide more  
371 reliable results in this case.

## 372 **4.2. Exploring the impact of buildings on the tidal signal propagation**

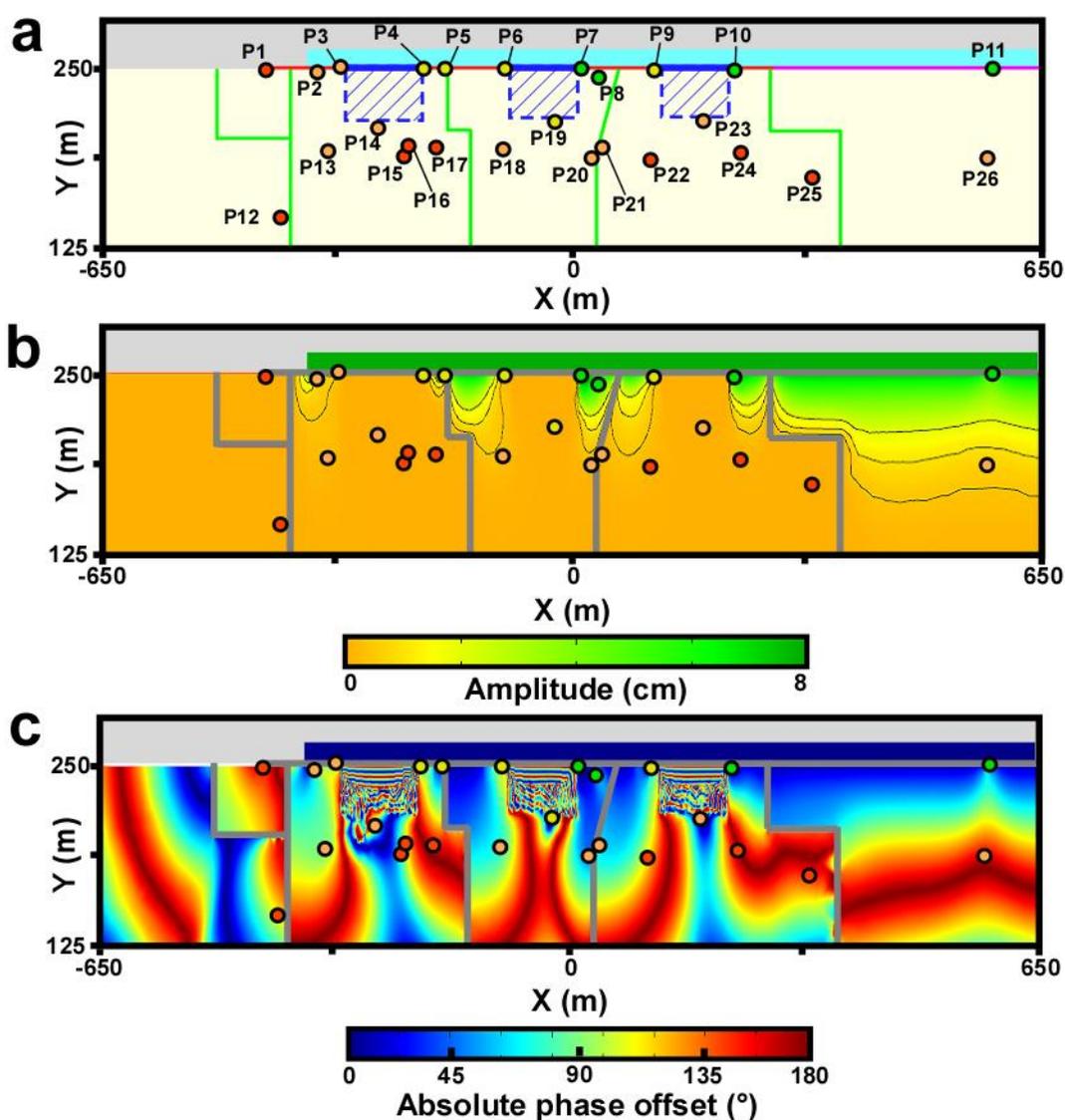
373 Figure 8 presents the simulations of amplitude and phase-offset responses obtained with the  
374 property maps of the model 'with buildings'.

375 The simulations run with the model are able to represent the complexity and the heterogeneity  
376 of the site. The amplitude of the tidal signal 'enters' the aquifer only through the buttress walls,  
377 between the buildings, thereby the amplitude response to this signal dissipates to an  
378 undetectable level very close to the channel in the building zones. Furthermore, the propagation  
379 of the signal in the aquifer along the buttress walls is also very different alongside the channel;  
380 it depends on the distribution of the properties of the aquifer in the model. The propagation of  
381 the tidal signal in the aquifer is then a combination of the efficiency of the hydraulic barriers  
382 and of the distribution of the property behind the barrier. In fact, it can be observed that the  
383 relatively less efficient parts of the hydraulic barriers highlighted in Figure 6 do not necessarily  
384 match with the areas where the tide signal can be the most observed in the aquifer. Therefore it  
385 is interesting to invert these entities simultaneously.

386 The phase-offset simulations permit better visualization of the propagation of the tidal signal.  
387 It shows that the signal enter through the buttress walls, then continues between the buildings  
388 and the impermeable screens orthogonal to the channel, and finally encircles the back of the

389 buildings and continues propagating behind. The phase-offsets simulated behind the buildings  
 390 can be delayed by an entire period compared to the channel signal according to these  
 391 simulations. This propagation behavior could explain why, even if the buildings completely  
 392 stop the tidal signal, one can still measure responses with a small phase-offset in piezometers  
 393 just behind these ones: they correspond to responses with a full cycle of delay (see P19 and  
 394 P23).

395



396

397 Figure 8: **a** The location of the piezometers in the (zoomed-in) zone near the channel. Maps of  
 398 the simulated **b** amplitude and **c** phase-offset responses with the property distributions ‘with  
 399 buildings’ presented in Figures 5 and 6.

400

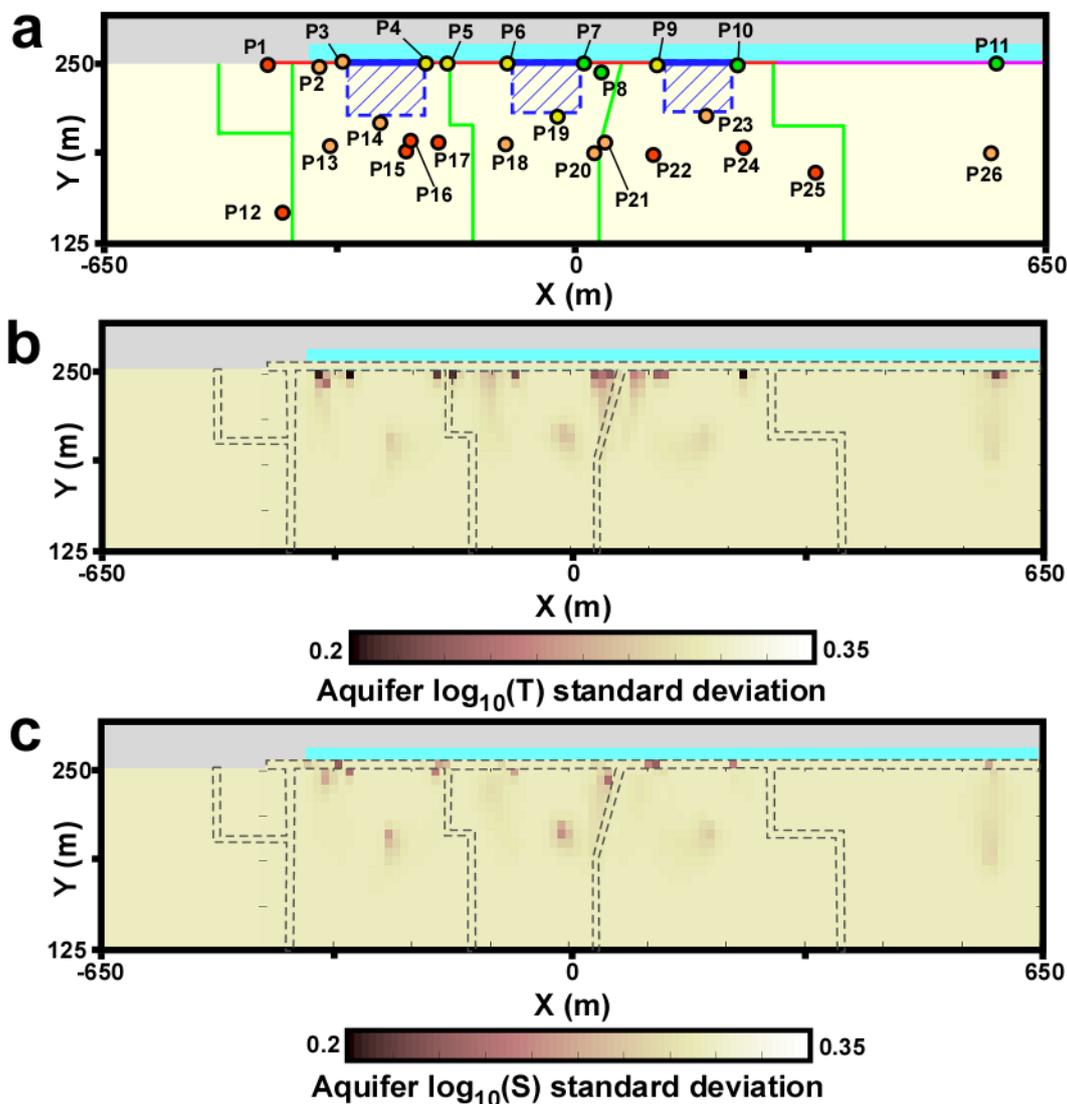
401 The maps of simulations also explain the differences of responses on each side of the  
402 impermeable screens orthogonal to the channel. These barriers have a non-negligible impact on  
403 the propagation of the signal in the aquifer, as can be clearly observed on the amplitude response  
404 simulation. Therefore, integrating the barriers as 1D elements in the model and the inversion  
405 process are very useful to explain some particular flow interactions between the aquifer and the  
406 anthropic structures (like the phase lag between the two very close piezometers P20 and P21).

### 407 **4.3. Quantifying uncertainties in the model around the channel and** 408 **buildings**

409 One crucial part of characterization is the study of the posterior covariance on the properties of  
410 the model, which provides the spatial uncertainties on the property values. Therefore, study of  
411 posterior covariance provides an indication of the spatial accuracy of the distributions found  
412 through the inversion process. Figure 9 shows the maps of standard deviations on the values of  
413 transmissivity and storativity calculated for the inversion ‘with buildings’.

414 First of all, one observes that the inverted distribution of properties is more accurate alongside  
415 the channel, which is logical because the measured responses in the aquifer are more important  
416 in this area. The building locations are associated with high uncertainty, which appears logical  
417 as they were voluntarily initially associated with very low transmissivities and high storativities.  
418 Thus, a slight modification of their property value will not generate a significant change on the  
419 flows. In the aquifer part, the transmissivities are better constrained than the storativities, while  
420 in the anthropic barriers parts the storativities are better constrained than the transmissivities.  
421 In both parts, the areas that are most constrained are located in the surroundings of the buildings  
422 and at the positions of the responding piezometers.

423



424

425 Figure 9: **a** The location of the piezometers in the (zoomed-in) zone near the channel. Maps of  
 426 the **b** transmissivity ( $T$ ) and **c** storativity ( $S$ ) standard deviations on the property distributions  
 427 ‘with buildings’ presented in Figures 5 and 6.

428

429 The inverted model seems to be reliable in the areas around the buildings, in the center part of  
 430 the model, between the anthropic structures. In fact, in these areas, the flows appear to be  
 431 constrained and there is a sufficient number of piezometers to characterize these flows.  
 432 However the areas on the left and on the right of the model seem to be rather unreliable. In these  
 433 two zones, there are only two piezometers to measure the aquifer responses and, if the properties

434 found in the direct vicinity of these two piezometers are well constraint, most of these areas  
435 cannot be well characterize because of a lack of information. In order to reduce the uncertainties  
436 of the model near the channel, more piezometer measuring responses in the aquifer would be  
437 necessary.

438 Finally, the parts of the site located far ( $> 100$  m away) from the channel, in which no oscillatory  
439 responses to the tidal signal could be measured in the piezometers, are not well constraint in the  
440 model, and therefore inaccurate. Thus, as already suggested in section '*Data processing*', the  
441 tidal signal from the channel does not permit characterization of areas very far away from it.  
442 Cardiff and Barrash (2015) proposed analytical tools in order to design punctual oscillatory  
443 sources for aquifer characterizations. At the site used in this study, the oscillatory source is not  
444 punctual and the aquifer heterogeneous, however these tools can give an idea of the distance  
445 investigable with the channel source. According to the period of tidal signal and the mean  
446 property values of the aquifer, the distance of signal propagation should be around 75 m, which  
447 seems coherent to what was observed. In order to better characterize the aquifer far from the  
448 channel, other sources of signals (such as active pumping or slug tests) would be required.

#### 449 **4.4. Discussion**

450 Some prerequisites and precautions should be considered when choosing to apply this  
451 characterization strategy. As shown in this paper, only a limited area alongside the channel can  
452 be characterized using tidal signals; more-inland zones require other sources of signal.  
453 Furthermore, in order to produce a reliable map of the property distributions, this method  
454 requires a larger number of measurement piezometers, spatially well-distributed along the  
455 channel. Finally, the incorporation of *a priori* knowledge regarding property distribution  
456 appears to be useful to generate more coherent and realistic models, as shown in this work with  
457 the integration of the building foundations as *a priori* information in the inversion process.

458 The presented characterization method, based only on the channel as a solicitation signal at the  
459 boundary of the model, permits characterization of the spatial distribution of the aquifer  
460 properties without having to perform an active solicitation techniques (pumping, slug tests,  
461 etc.), which is especially interesting in cases where the use of such techniques is limited or  
462 impossible. The hydraulic characterization presented in this study also presents the advantage  
463 of simultaneously characterizing the properties of the aquifer (in 2D) and of the anthropic  
464 structures and barriers (in 1D) alongside the channel. This can enhance the success of the  
465 inversion process and localize the relatively less efficient segments of the barriers.

## 466 **5. Conclusion**

467 The tidal signal carried by the channel connected to the sea has been exploited in this study to  
468 characterize a highly anthropized coastal field, without any active solicitation (such as pumping  
469 tests). Data processing on the piezometric measurements in the aquifer enabled extraction of  
470 the groundwater responses, specifically to this tidal signal, in terms of amplitude and phase-  
471 offset values. The numerical model, solved in a frequency domain and associated to property  
472 distributions generated by inversion of the responses to the tidal signal, could finally allow for  
473 an interpretation of the propagation of the signal through the anthropic barriers and in the  
474 aquifer. The integration of the anthropic structures as 1D elements in the model and of *a priori*  
475 information of the buildings foundations in the inversion process generate a more realistic  
476 model, able to simulate the complex behavior of the propagation of the tidal signal between the  
477 buildings and barriers within the aquifer. The maps of simulated propagation of signal,  
478 generated from the inverted model of properties, represent, in the end, an interesting tool in  
479 order to understand and interpret the responses measured punctually in the field. These maps  
480 can help to understand how the groundwater flows under the site, near the channel, which  
481 allows for better water resource management.

482

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