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## **Clogging detection and productive layers identification along boreholes using Active Distributed Temperature Sensing**

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1 Highlights

2 **Clogging detection and productive layers identification along bore-**  
3 **holes using Active Distributed Temperature Sensing**

4 J.Godinaud, M.Klepikova, F.Larroque, N.Guihéneuf, A.Dupuy, O.Bour

- 5 • Active Distributive Thermal Sensing experiment achievement at ATES
- 6 site
- 7 • Determination of thermal conductivity and groundwater flux along
- 8 boreholes
- 9 • Identification of clogging location along boreholes

10 Clogging detection and productive layers identification  
11 along boreholes using Active Distributed Temperature  
12 Sensing

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15 **Abstract**

16 Fiber-Optic Active Distributed Temperature Sensing (FO-ADTS) experi-  
17 ments were performed on an Aquifer Thermal Energy Storage system (ATES)  
18 site located on the university campus of Bordeaux, France. The experiments  
19 consisted in heating the steel core of the FO cable while monitoring the  
20 rate of temperature increase during the heating periods. The changes in  
21 temperature, that were monitored through time at every depth under var-  
22 ious hydraulic conditions and in different boreholes, were used to evaluate  
23 both aquifer properties and wells conditions. A first ADTS experiment was  
24 conducted under cross borehole configuration using a pumping well and a  
25 monitoring well separated by a distance of 8.5 meters. Then, to check the  
26 reciprocity of the results, a second experiment was conducted by switching  
27 the monitoring and the pumping well. The results obtained through the use  
28 of analytical solutions for reproducing and interpreting the data lead to the  
29 following conclusions: (i) ADTS can be used to estimate both thermal con-

ductivity and Darcy velocity distribution along boreholes, crucial properties for ATES performance. (ii) The proposed method is a promising tool to detect clogging locations in the boreholes when it occurs. This can be of great practical interest to maintain systems performance, since, once FO cables deployed, experiments could be easily repeated without opening boreholes and stop the system operation.

*Keywords:*

Distributed Temperature Sensing, Groundwater Flux, Thermal Conductivity, Clogging, ATES

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## 1. Introduction

Aquifer Thermal Energy Storage (ATES) is an open loop geothermal system involving at least two reversible boreholes [Fleuchaus et al., 2018]. This technology uses the subsurface as transient long-term storage of cold and warm water and it gains more and more popularity with a great potential to reduce green house gas emissions of the building sector [Vanhoudt et al., 2011, Gao et al., 2017, Ghaebi et al., 2017, Schüppler et al., 2019, Stemmler et al., 2021].

ATES performance is highly sensitive to hydrogeological conditions. It requires good aquifer permeability to pump and inject water into the aquifer, low natural groundwater flow to avoid stored energy losses due to advection and/or thermal interaction between wells. During system operation, storage efficiency and energy recovery rate depend on the cold and warm thermal

52 plumes extension [Bloemendal and Hartog, 2018]. The spatiotemporal dis-  
53 tribution of temperature is particularly impacted by aquifer heterogeneity  
54 especially regarding the groundwater flux and thermal properties distribu-  
55 tion [Ferguson, 2007, Sommer et al., 2013, Bridger and Allen, 2014, Ganguly  
56 and Mohan Kumar, 2014, Possemiers et al., 2015, Visser et al., 2015, Nguyen  
57 et al., 2016, Bloemendal and Hartog, 2018].

58 ATEs performance also depends on wells sustainability which can be im-  
59 pacted by their aging. Among the main issues, corrosion, biological, chemical  
60 and physical clogging are major problems which could lead to well damages  
61 and performance decrease [Fleuchaus et al., 2018, Bloemendal and Olsthoorn,  
62 2018]. The causes and consequences of the boreholes clogging are well docu-  
63 mented for open loop systems [Bakema, 2001, Song et al., 2020]. A large clog-  
64 ging development is an additional source of geothermal system performance  
65 decrease. Quantification of the subsurface heterogeneity, and the surveillance  
66 of clogging evolution in wells, are therefore major concerns on ATEs site.

67 Classically, thermal and hydrodynamic properties of aquifers are char-  
68 acterized from laboratory measurements on core samples. Moreover, some  
69 field surveys may be used in the context of ATEs characterization. Among  
70 these surveys, pumping tests give an average value of aquifer transmissivity  
71 and specific storage. Their monitoring time ranges classically between 1 and  
72 3 days and their well known interpretation provides a first overview of hy-  
73 drogeological properties and context of a site [Kruseman and Ridder, 1994].  
74 Flowmeter logs are suited to obtain the vertical flow distribution at a particu-

75 lar point and can provide information on fracture connectivity, transmissivity  
76 and storativity distribution [Molz et al., 1994, Paillet, 1998, Roubinet et al.,  
77 2015]. These tests are simple to realize and can be performed in short time.  
78 Heat or solute tracer tests are used to investigate groundwater velocity, ther-  
79 mal and hydraulic dispersivity, or location of preferential groundwater paths  
80 [Bodin et al., 2003, Klepikova et al., 2016, Irvine et al., 2015]. But they are  
81 more difficult to realize, and a robust interpretation could require a lot of  
82 observation points, as well as comprehensive numerical modeling. Thermal  
83 Response Tests (TRT) are used to estimate the average thermal conductivity  
84 of aquifers at the vicinity of the tested well, but the data collection could  
85 require a long time [Beier et al., 2011, Dong et al., 2022]. Finally, cores  
86 collection is financially costly, time-consuming, and their analysis provides  
87 only local information which could not be representative of the global in-site  
88 aquifer dynamics [Sharqawy et al., 2013].

89 Preventive actions to tackle clogging development include reduction in  
90 the frequency of pump starts and stops, underground removal of iron, avoid-  
91 ing possible oxygen infiltration or reduction of water turbidity and organic  
92 content. Nevertheless, a certain clogging extension cannot be avoided during  
93 the recharge process, thus leading to the decrease of geothermal system per-  
94 formance [Song et al., 2020]. Surveillance of the clogging evolution is thus a  
95 major challenge for ATEs systems, and developing adapted countermeasures  
96 on site could significantly help to maintain their performance. Recently, a  
97 strategy was developed to follow its evolution [Gjengedal et al., 2020]. The

98 surveillance procedure aims to conduct a step-test with incremental increases  
99 in the groundwater flow rate while measuring the pressure and temperature  
100 responses in the system components. Nevertheless, it does not focus on clog-  
101 ging locations in the well, but gives an overall view of each component of the  
102 geothermal system (production wells, submersible pump and groundwater  
103 heat exchanger).

104     Distributive Thermal Sensing with Fiber Optic cable (FO-DTS) opens a  
105 timely opportunity to improve our understanding of the functioning of ATEs  
106 systems. This technology enables to collect efficiently long data set and to  
107 monitor dynamics process [Bense et al., 2016]. For geothermal application,  
108 it was first used to monitor temperature variations along production bore-  
109 holes [Hurtig et al., 1996]. DTS methods have seen further improvements  
110 with the use of the active mode (ADTS). It consists on deploying a heat  
111 source in the well and monitoring the induced temperature changes [Bense  
112 et al., 2016]. The temperature elevation induced by the heat source and the  
113 subsequent cooling directly depends on thermal properties of the porous me-  
114 dia and on water flux dissipating heat by advection. Among other, it can  
115 be used to achieve Enhanced Thermal Response Test (ETRT) to establish  
116 thermal conductivity profile for Borehole Heat Exchanger (BHE) application  
117 [Freifeld et al., 2008, Huber and Arslan, 2012, Vélez Márquez et al., 2018,  
118 Zhang et al., 2020, Hakala et al., 2022]. Furthermore, the method proved  
119 its ability to measure groundwater flux distribution in the subsurface [Read  
120 et al., 2014, Bakker et al., 2015, des Tombe et al., 2019]. Recent laboratory

121 and field experiments demonstrate that analytical methods can be used to  
122 inspect the distribution of thermal conductivity and Darcy velocity along  
123 a fiber positioning in saturated porous media [Simon et al., 2021, del Val  
124 et al., 2021]. These works enable the generalization of ADTS experiments  
125 interpretation.

126 Apart from aquifer thermal properties, the thermal conductivity profile  
127 established in a borehole could be also of major interest to inspect eventual  
128 low anomalies due to clogging development. Indeed, the value of thermal  
129 conductivity for clogging materials such as bentonite, clay or porous iron  
130 hydroxides provides a particular low signature useful for identification [Tang  
131 et al., 2008, Cho et al., 2008, Gjengedal et al., 2020, Dalla Santa et al., 2020].

132 To our knowledge, FO-ADTS experiments in boreholes have never been  
133 performed with a purpose of detecting both clogging development and pro-  
134 ductive layers. Most of the experiments achieved in boreholes mainly focus  
135 on fractured zone identification [La Bernardie et al., 2018, Maldaner et al.,  
136 2019, Klepikova et al., 2022], Darcy velocity estimation [Selker and Selker,  
137 2018, del Val et al., 2021] or aquifer thermal conductivity [Zhang et al., 2020,  
138 Hakala et al., 2022].

139 In this context, a cross-borehole ADTS experiment was carried out on a  
140 site located at the university of Bordeaux in France, and planned to be ex-  
141 ploited by a new ATEs. The test was realized under constant pumping rate  
142 condition and replicated in two different boreholes to verify the reciprocity of  
143 the data. The main objectives were **(i)** to characterize the vertical distribu-

144 tions of thermal conductivity and Darcy velocity in two different boreholes,  
 145 (ii) to reveal the preferential water pathways during injection (iii) to demon-  
 146 strate the potential of ADTS to detect clogging area along well screens.

## 147 2. Experimental Site

### 148 2.1. Context

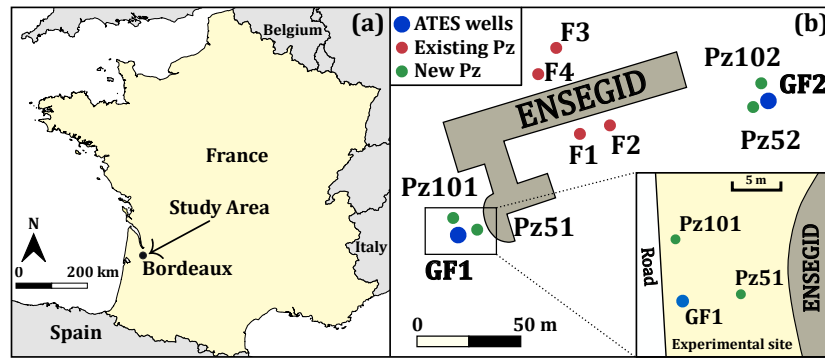


Figure 1: (a) Location of experimental area, (b) ENSEGID site map with boreholes location and focus on the experimental area

149 The study area is located at the university of Bordeaux (Pessac, France,  
 150 (Figure 1a), on the site of the Ecole Nationale Supérieure en Environnement  
 151 Géosourçes et Ingénierie du Développement Durable (ENSEGID). An  
 152 ATES system was designed to supply both cooling and heating to a new  
 153 building of 3600 m<sup>2</sup>. The ATES consists of a pair of 70 m deep reversible  
 154 pumping/injection wells, GF1 hot well and GF2 cold well, located 145 me-  
 155 ters apart (Figure 1b). In addition to the production wells, four piezometers  
 156 (Pz51, Pz101, Pz52 and Pz102) were created close to the main wells to mon-  
 157 itor thermal plume extension and to control piezometric heads. Piezometers

158 Pz101 and Pz51 are used for the ADTS experiment. They are separated  
159 by a distance of 8.5 m and located 6.0 m and 6.5 m apart from the ATES  
160 hot production well GF1 . They were drilled to 66 m and 70 m deep re-  
161 spectively. Our experiments were achieved 8 months before the beginning of  
162 ATES operation.

163 Located in the North Aquitaine Basin, the experimental site corresponds  
164 to a large multi-layered aquifer system. The actual structure of this basin  
165 is the result of Pyrenees retro-foreland basin developed from the Campanian  
166 to the Miocene [Labat et al., 2021]. The local geology corresponds to the  
167 top of the system formed by a succession of sedimentary deposits during  
168 multiple transgression/regression periods, leading to a vertical heterogeneous  
169 sequences of limestone, sandstone and clay from Eocene to Plio Quaternary  
170 times [Larroque et al., 2013]. The proximal shore location of the site during  
171 Oligocene period results in highly horizontally and vertically heterogeneous  
172 limestone deposits [Sztrákos and Steurbaut, 2017]. A part of the Oligocene  
173 formation, composed by highly porous and permeable fossiliferous limestones,  
174 constitutes the ATES aquifer target. Around the experimental site, the deep  
175 aquifer is confined, as pointed out by seasonal artesianism. Near the surface  
176 level, a 10 meters thick unconfined aquifer, made of Plio Quaternary sand  
177 and clay deposits, covers the Oligocene formation. At the site location, the  
178 Oligocene aquifer limestone is crossed from 12 m depth to 68 m depth.

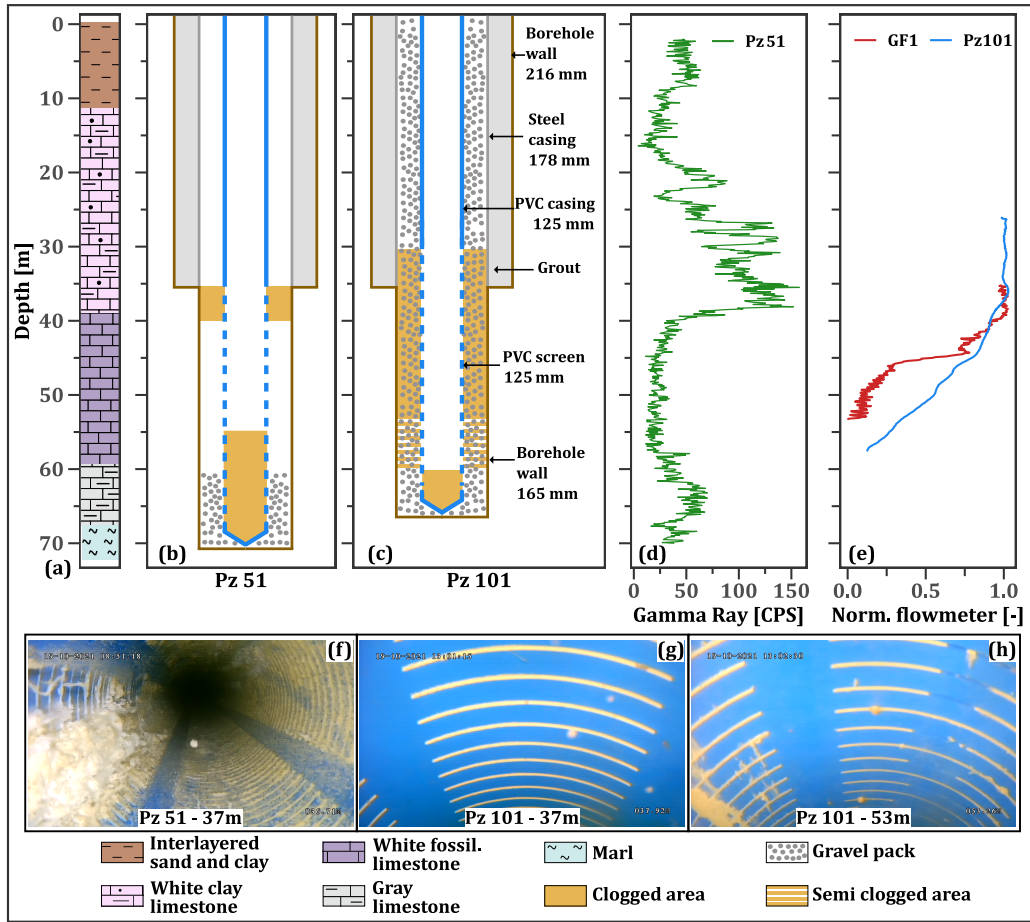


Figure 2: Field data : (a) Geological section of the site, (b) and (c) technical logs of piezometers with clogged area detect during video inspection, (d) Pz51 gamma ray, (e) GF1 and Pz101 flowmeter logs, and (f,g,h) video inspection screenshots

179 *2.2. Field data*

180 The available field data, including gamma ray log, flowmeter logs and  
 181 drill cuttings observations, highlight a heterogeneous limestone aquifer with  
 182 a vertical and horizontal unequal distribution of incoming water fluxes. The  
 183 layer crossed between the depth of 40–60 m (Figure 2a), is made of fossilifer-  
 184 ous white limestone. A developed porosity is identified from microscopic drill

185 cuttings observation. In this layer, the Pz51 Gamma Ray values fluctuate  
186 around an average of 25.0 cps, which indicates a low clay content (Figure 2d).  
187 The GF1 flowmeter reveals that the incoming water is located from the depth  
188 of 40 m to 55 m. In this area, a layer of 2 meters thick between the depth  
189 of 44 m and 46 m produces about the half of the total discharge (Figure 2e).  
190 Another flowmeter realized in Pz101 one year after the end of borehole works  
191 completion (and before the beginning of ATES operation) indicates a more  
192 homogeneous flux distribution along this borehole (Figure 2e). Between the  
193 depth of 60 m and 67 m, the drill cuttings observations emphasize gray  
194 limestones, a less developed porosity and a significant clay content. From  
195 67 m, to 71 m, blue marl is encountered. A mean transmissivity value of  
196  $7.0 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$  is estimated from a two days pumping test in GF1.

197 Borehole camera inspections show the presence of clogging material in  
198 piezometers Pz101 and Pz51 (Figure 2f, g and h). From the depth of 35  
199 m to 39 m, the Pz51 screens are totally clogged by a mix of yellow brown  
200 bentonite clay/mud and white bio-fouling bacteria (Figure 2f). The screens  
201 are clean in the interval length 40–54 m. The Pz51 bottom is filled with  
202 clay and bentonite and encountered at the depth of 54.5 m instead of the 71  
203 m initially drilled. We believe that the main reason for the fast clogging is  
204 related to the fact that these wells are planned only for monitoring purpose  
205 . As a consequence, the piezometers were not sufficiently developed. As for  
206 Pz101, the screens are totally clogged by bentonite and mud from the depth  
207 of 35 m to 53 m (Figure 2g). Below the depth of 53 m to the Pz101 bottom

208 at 60 m, the screens are partially clogged (Figure 2h). The clogged intervals  
209 of the piezometers are represented on the technical logs (Figure 2b and c).

### 210 **3. Experiment and methodology**

#### 211 *3.1. Experimental set up*

212 ADTS experiments were conducted in Pz101 and Pz51. A loop of BRUsens  
213 fiber-optic cable (SOLIFOS - Fiber Optic Systems AG, Switzerland) was  
214 lowered to their annular space. It contains two multi-mode fibers encased  
215 in a sealed stainless steel capillary and covered by wire rope and a PVC  
216 jacket (Figure 3a). Two electrical cables were connected to the steel armor  
217 of both fiber branches of the loop, to allow the injection of electricity from a  
218 power controller. These connections were further sealed by epoxy resin. The  
219 induced temperature variation was monitored with a Silixa XT DTS unit  
220 reporting temperature every 25 cm at a 2 min sampling interval in Pz51 and  
221 1 min sampling interval in Pz101 (Figure 3b).

222 In order to ensure contact with the porous media, while deployed in the  
223 borehole, each branch of the FO cable was slightly stretched and attached  
224 outside the polyvinyl chloride (PVC) tube every 3 meters (Figure 3c). This  
225 installation was similar to a previous study in 25 m depth boreholes [del Val  
226 et al., 2021]. For both piezometers, 50 meters of FO cable of each side of the  
227 loop remained outside the borehole for connection to the DTS unit, and for  
228 calibration purposes. Once the whole equipment installed, the gravel pack  
229 was added down, which embedded the FO cable in the gravel and prevented

230 any cable shaking.

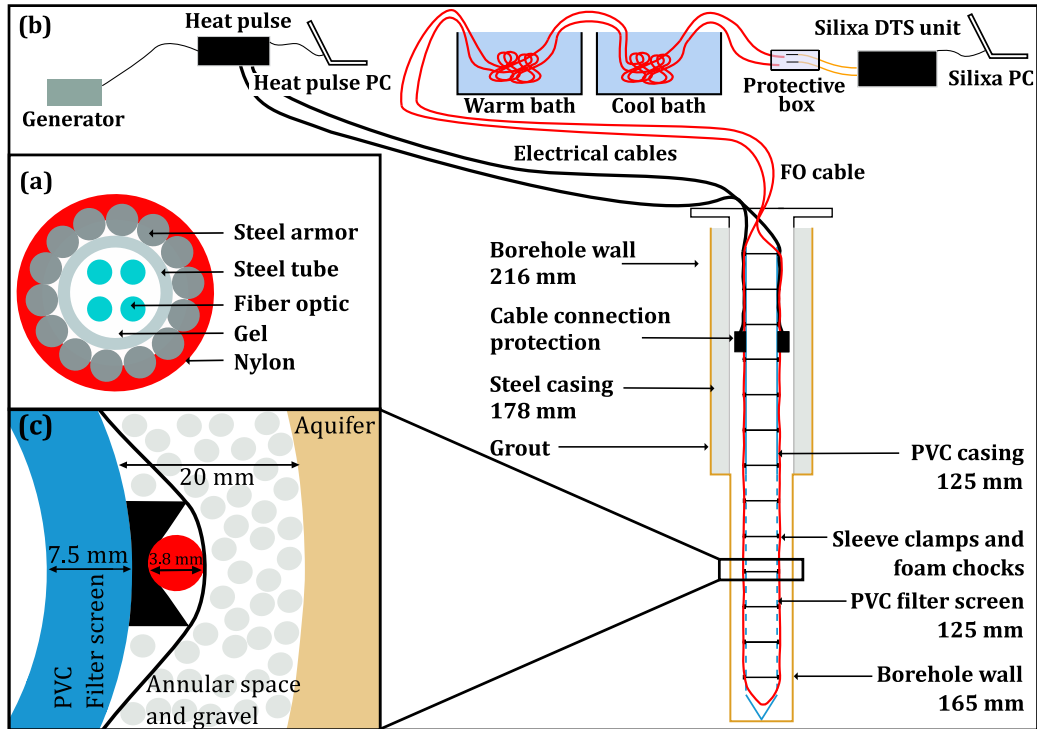


Figure 3: Device installation scheme : (a) transverse section of the FO cable, (b) scheme of experimental configuration with acquisition well and FO-DTS set up, (c) traverse borehole section representing fiber configuration in annular space

### 231 3.2. Temperature calibration process and DTS spatial resolution

232 During the experiment, 10 meters of each branch from sticking out cables  
233 were immersed into separate warm and cold calibration baths for tempera-  
234 ture calibration purposes. In order to cover the full range of temperatures  
235 that could be expected to be measured along the fiber optic cable, the cold  
236 bath was filled with ice and the warm bath was equipped with a resistance  
237 to maintain water temperature at 31°C (Figure 3b). The temperature was

238 recorded in each bath with a PT100 probe (0.1°C accuracy) and two RBR  
239 SoloT probes (0.002°C accuracy). The temperature in both baths was ho-  
240 mogenized with small aquarium bubblers. The loop configuration of the fiber  
241 in the boreholes allowed to create a double-ended connection providing accu-  
242 rate temperature measurements under field conditions [van de Giesen et al.,  
243 2012]. The Python toolbox [des Tombe et al., 2020] was used to check the  
244 quality of the DTS measurement and indicated a good calibration of the  
245 temperature measured by the DTS device.

246 The DTS spatial resolution (S.R) during the experience was estimated  
247 from the classical 90% step change [Tyler et al., 2009] and the derivative  
248 method [Simon et al., 2020]. For Pz101, the S.R was estimated between 0.9  
249 and 1.1 m. As the sampling time (S.T) was twice larger for Pz51 experiment,  
250 the S.R was better and range from 0.7 to 0.9 m. The S.R of these experiments  
251 were more precise than the 2–3 m S.R reported in the study of Tyler [Tyler  
252 et al., 2009] and slightly less precise than the 0.5–0.9 m S.R reported in the  
253 laboratory study of Simon [Simon et al., 2020].

### 254 *3.3. Experiments proceedings*

255 The experiment was ran under cross-borehole configuration. It is a com-  
256 mon practice for integrated aquifer characterization. It is an efficient method  
257 to explain complex hydraulic behavior of aquifers and investigate preferential  
258 flow-path in heterogeneous contexts [Butler and Zhan, 2004, Le Borgne et al.,  
259 2006a,b, Audouin and Bodin, 2008, Brauchler et al., 2010, Lods et al., 2020,

260 Aliouache et al., 2021]. This configuration is therefore of great interest to  
261 study thermal transfer by advection at the aquifer scale. The cross-borehole  
262 configuration was replicated into Pz101 and Pz51 to verify the reciprocity of  
263 the acquired data. The reciprocity can be used to interpret the dynamic of  
264 the aquifers and highlights continuity or not of the hydraulic system [Hariga  
265 et al., 2010, Delay et al., 2011, 2012, Marinoni et al., 2016, Sanchez-Vila  
266 et al., 2016].

267 The experiment started once the hydrodynamic pseudo-steady state was  
268 reached. The first stage consisted in heating the steel mantle of the fiber in  
269 the well Pz101 with a constant injection rate of power  $P$  through electrical  
270 cables controlled by the Heat Pulse power controller. At the same time, the  
271 neighboring piezometer Pz51 was pumped at a constant rate  $Q$  varying in  
272 between 4.5 and 4.6  $m^3/h$  depending on the experiment (Experiment 1 in  
273 Figure 4). The water level was monitored with vented Level Troll probes (In  
274 Situ) in both piezometers. The temperature evolution along the FO cable  
275 induced by the heat injection was monitored by the DTS device. At the  
276 end of the first stage, without stopping the heating of the fiber, the pumped  
277 water was injected in the monitoring well to monitor thermal signals induced  
278 by the injection (Experiment 2 in Figure 4). The injected water came from  
279 the aquifer under natural conditions, consequently it was colder than the  
280 water warmed by the fiber in the monitoring piezometer. Experiments 3 and  
281 4 (Figure 4) correspond to ADTS experiment replicated in Pz51.

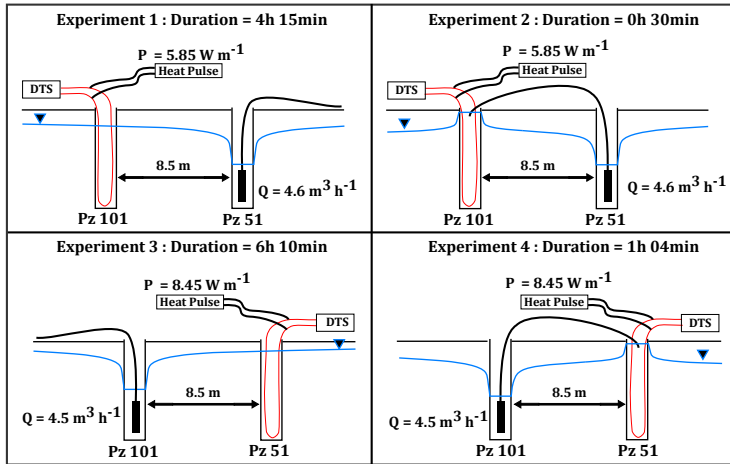


Figure 4: Scheme of the four experiment configurations with the indicated injected power by the heat pulse  $P$  and the pumping rate  $Q$ .

#### 282 4. Experimental data analysis

283 Before the heating phase, the initial temperature distribution was recorded.  
 284 It represented a C-shape with a minimum temperature of  $15.4^{\circ}\text{C}$  between  
 285 the length interval of 35–65 m depth (Figure 5a). Such a temperature pro-  
 286 file is typical for subsurface temperature regime influenced by an increase  
 287 in ground surface temperature caused by global warming and/or urbaniza-  
 288 tion[Dědeček et al., 2012, Visser et al., 2015, Bayer et al., 2016]. Figure 5b  
 289 represents transient temperature profiles along Pz51 (455 curves) acquired  
 290 during the heating phase of the experiment.

291 As pointed out by the heat map, the U-shape of the cable provided two  
292 similar data sets at each sampling depth in Pz51. Data from Pz101 (423  
293 curves, not displayed in Figure 5) are analyzed further in the manuscript.  
294 When the heating started (Experiment 1 and 3), there was a quick tem-  
295 perature increase along the cable, followed by a phase of slow change. As  
296 expected, differences of temperature elevation along the wells were observed  
297 due to thermal and hydrodynamic properties contrasts of aquifer layers [Si-  
298 mon et al., 2021, Zhang et al., 2020]. In some intervals, like 35 - 40 m depth  
299 the temperature reached a value of 25 °C, whereas at 45 m depth the temper-  
300 ature quickly stabilized around 18 °C. Such differences in thermal behavior  
301 along the well are analyzed in the following sections. During the water in-  
302 jection (Experiments 2 and 4) the temperature changes were less significant.  
303 Once the electrical power switched off, the temperature along the FO cable  
304 decreased drastically.

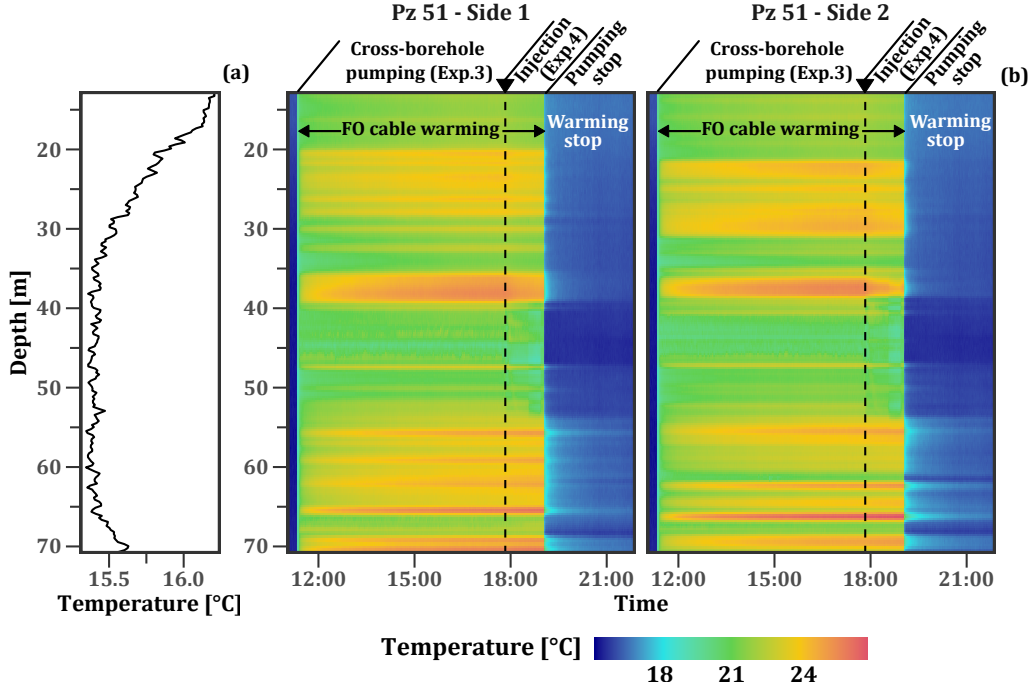


Figure 5: Temperature distribution along the FO cable in Pz51: (a) natural *in-situ* profile before the heating and (b) temperature variation with both time and depth along the two side of the FO loop. The temperatures measured at each side of the U cable are similar

305 *4.1. Preferential water flux pathways during reinjection*

306 The temperature anomalies measured during reinjection Experiments 2  
 307 and 4 informed about the preferential flow paths in front of the screens during  
 308 injection. These anomalies were emphasized by the relative temperature  
 309 anomaly  $\Delta T_{inj}$  (Equation 1) induced by the injected water:

310 
$$\Delta T_{inj} = T_t - T_{inj.start} \quad (1)$$

311 where  $T_{inj.start}$  is the temperature profile just before the beginning of water  
 312 injection, and  $T_t$  the temperature profile measured at the time  $t$  after the  
 313 beginning of the injection. The evolution of  $\Delta T_{inj}$  profiles revealed three  
 314 different zones in both piezometers (Figure 6a and c).

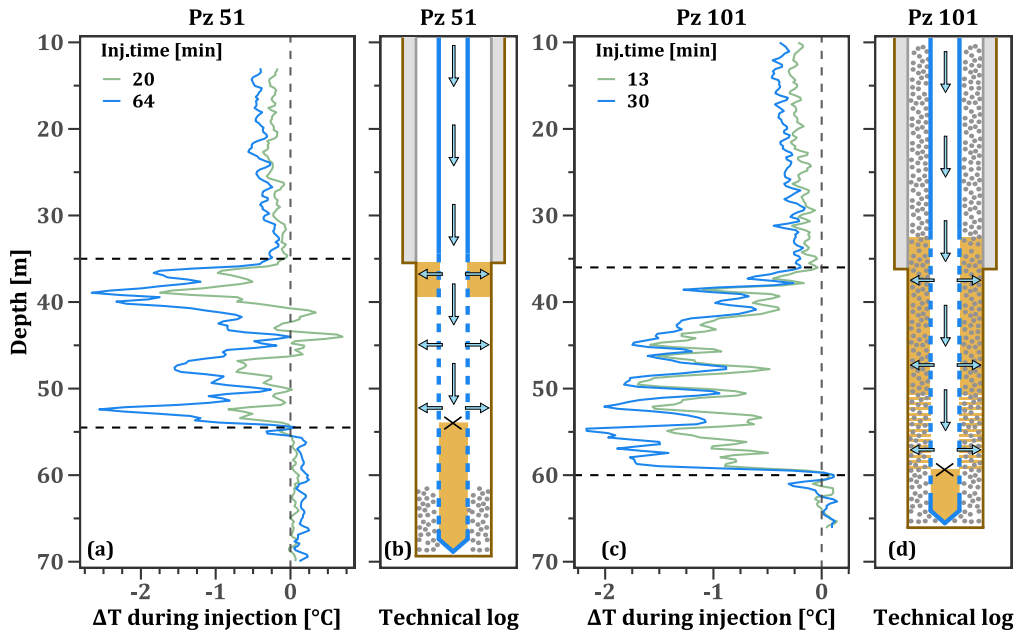


Figure 6: Experimental injection results : (a) and (c) relative temperature anomaly profiles  $\Delta T_{inj}$  at different times since the beginning of the injection; (b) and (d) technical log with identified clogged area from video inspection and flux pathway deduced from injection experiment represented by blue arrows

315 First, above the screens, i.e., at 35 m depth, in the grouted area, the  
 316 injected water induced a slight temperature decrease less than  $0.5^\circ\text{C}$  in both  
 317 wells. This was related to conductive heat transfer due to colder water injection.  
 318 For depths greater than 54.5 m in Pz51 and 60 m in Pz101, the water

319 temperature continued to increase due to the cable heating. It indicated  
320 that, the injected water did not influence the evolution of borehole temper-  
321 ature. The latter means that the injected water did not infiltrate below  
322 these depths. Finally, in the middle parts of both wells, an overall significant  
323 temperature decrease induced by the local flow increase occurred in both  
324 piezometers. The water infiltration areas are identified on the technical log  
325 of both piezometers (Figure 6b and d). The thermal response was heteroge-  
326 neous along the screens in both piezometers. For example, the layers at the  
327 depths of 39 m and 53 m in Pz51, or 54 m in Pz 101 were more sensitive to  
328 the cooling and reached a  $\Delta T_{inj}$  of  $-2.0^\circ\text{C}$ . Other layers, especially in Pz51  
329 (41, 44 and 50 m), were barely affected by the cooling.

330 The short duration of the Experiments 2 and 4 (30 min and 64 min  
331 respectively) did not allow a quantitative interpretation of the temperature  
332 transients and only provided a qualitative overview about zones of enhanced  
333 groundwater flow.

## 334 *4.2. Use of analytical solutions for parameter distribution estimation*

### 335 *4.2.1. General interpretation framework*

336 ADTS data interpretation of Experiment 1 and Experiment 3 consisted  
337 on estimating vertically distributed parameters  $\lambda$  and  $q$  in the observation  
338 borehole. The parameters were calculated at each sampling depth. It was  
339 achieved through the assessment of experimental temperature evolution curves  
340 measured by the DTS device, following the theoretical approach developed

341 by [Simon et al., 2021]. The interpretation framework was inspired from the  
 342 one proposed by a free available Matlab Toolbox Simon and Bour [2022], and  
 343 detailed further.

344 The two-dimensional heat transport in saturated porous media (Equa-  
 345 tion 2) involving conduction and advection processes is expressed as [Carslaw  
 346 et al., 1959] :

$$347 \quad \frac{\partial T}{\partial t} = D_t \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) - q \frac{\rho_w c_w}{\rho_b c_b} \frac{\partial T}{\partial x}, \quad (2)$$

348 where  $T$  is the temperature [K],  $x$  and  $y$  are the coordinates [m],  $q$  is the  
 349 Darcy velocity [ $\text{m s}^{-1}$ ],  $\rho_b c_b$  the volumetric heat capacity of the rock/fluid ma-  
 350 trix [ $\text{J m}^{-3} \text{K}^{-1}$ ],  $\rho_w c_w$  the volumetric heat capacity of the water [ $\text{J m}^{-3} \text{K}^{-1}$ ].  
 351 Ignoring thermal dispersion is a common practice for the interpretation of  
 352 ADTS experiments [Bakker et al., 2015, Simon et al., 2021, del Val et al.,  
 353 2021]. The consequences of this choice on the estimation of the parameters  
 354 are discussed in subsection 5.2. Therefore, in Equation 2, only thermal dif-  
 355 fusivity  $D_t$  [ $\text{m}^2 \text{s}^{-1}$ ] is involved. It depends on  $\lambda$  the bulk thermal conductivity  
 356 [ $\text{W m}^{-1} \text{K}^{-1}$ ] and is expressed as :

$$357 \quad D_t = \frac{\lambda}{\rho_b c_b}. \quad (3)$$

358 Considering whether or not natural flow in the aquifer occurred, Equation 2  
 359 could be solved for a linear heating source involving the Instantaneous Line  
 360 Source model (ILS) or Moving Instantaneous Line Source model (MILS)  
 361 [Carslaw et al., 1959]. The ILS solution expressed as follows (Equation 4),

362 considers no-flow within the aquifer and is the solution to Equation 2 without  
 363 considering the second term:

$$364 \quad \Delta T(r, t)_{ILS} = \frac{P}{4\pi\lambda} \left[ E_i \left( \frac{-r^2}{4tD_t} \right) \right], \quad (4)$$

365 where  $\Delta T$  is the temperature evolution,  $P$  [ $\text{W m}^{-1}$ ] is the constant heating  
 366 power per unit length,  $r^2 = x^2 + y^2$  is the distance from the heating source.

367 The MILS solution (Equation 5) is adapted from the ILS and considers  
 368 uniform flow across the heat source to take into account heat transfer by  
 369 advection. It is expressed as :

$$370 \quad \Delta T(r, t)_{MILS} = \frac{P}{4\pi\lambda} \exp \left[ \frac{qr}{2D_t} \frac{\rho_w c_w}{\rho c} \right] W(\alpha, \beta) \quad (5)$$

371 with  $W(\alpha, \beta)$  the Hantush well function [Hantush, 1956].  $\lambda$  and  $q$  are esti-  
 372 mated from these two solutions.

373 The previous equations did not consider thermal effects induced by the  
 374 heating of the cable itself and the borehole material configuration. Just  
 375 after heat injection in the FO cable, the temperature increase was mainly  
 376 associated, first, to the conductive skin effect in the FO cable components  
 377 and secondly to the borehole material arrangement [del Val et al., 2021,  
 378 Simon et al., 2021]. It generated a rapid increase of the temperature during  
 379 the first time after heat injection. The effect of the cable was the same  
 380 along the borehole. Nevertheless, the effect of the borehole material on the  
 381 temperature increase could be different along the FO, depending on the cable

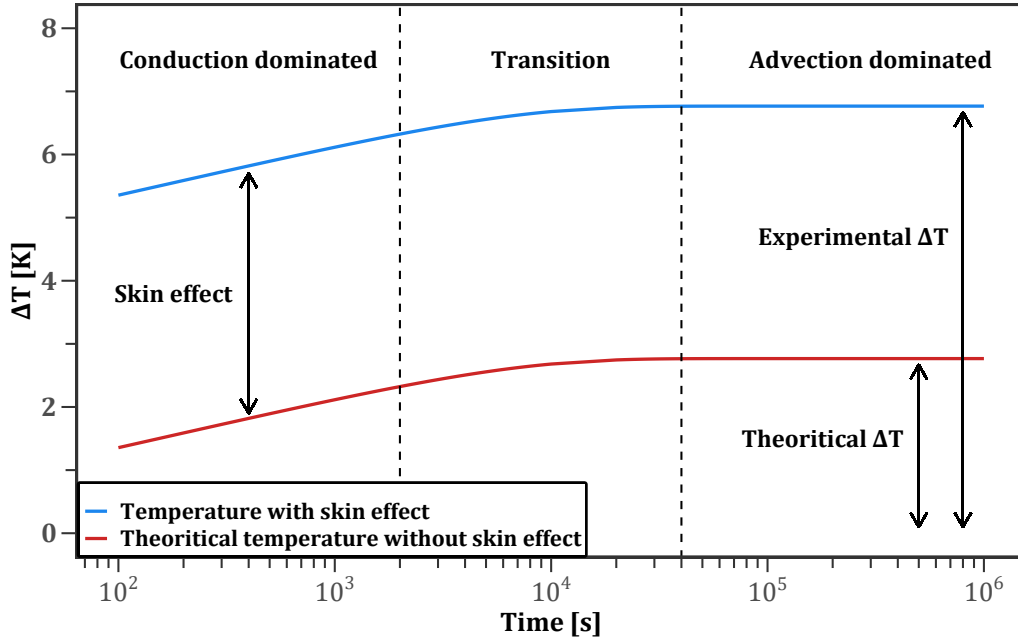


Figure 7: Theoretical temperature evolution in response to a heat pulse in saturated porous media with and without skin effect of the FO cable (adapted from [del Val et al., 2021])

382 position in the gravel pack and mud and its relative distance to the PVC  
 383 tube. This aspect lead to a difference between the theoretical temperature  
 384 calculated with ILS and MILS and the  $\Delta T_{exp}$  measured by FO-DTS. This  
 385 difference was taken into account in a  $\Delta T_{FO}$  term (Figure 7). Thus, to model  
 386 the temperature increase during the experiment,  $\Delta T_{FO}$  was added to the ILS  
 387 and MILS solutions. This was solved by trial/error adjustments between ILS  
 388 model and experimental data.

#### 389 4.2.2. Parameters quantification

390 The ILS and MILS solutions were adjusted on the experimental data  
 391 to estimate the  $\lambda$  and  $q$  values associated with the temperature evolution

392 (Figure 8). The method consisted in reducing the Root Mean Square Error  
393 between the observed and modeled temperature using the Brent algorithm  
394 [Brent, 1974]. Four typical thermal behaviors were identified during the  
395 ADTS experiments, ranging from no-flow and low-flow towards medium-flow  
396 and high-flow.

397 For no-, low- and medium- Darcy velocity ( $< 2.0 \times 10^{-5} \text{ m s}^{-1}$ ), the ex-  
398 perimental points before 1000 seconds were assimilated to the skin effect.  
399 Thus, these points were excluded from  $\lambda$  fitting and estimation procedure  
400 (Figure 8 a-c). When only conductive heat transfer occurred, (i.e. no-flow)  
401 the temperature increased linearly along a log time scale during the whole  
402 experimental time (Figure 8a). In this case, the ILS solution was used to es-  
403 timate  $\lambda$ . Advection transfer generated a transition phase until temperature  
404 stabilization (Figure 8b and c), and both analytical solutions were used to  
405 estimate  $\lambda$  and  $q$ .

406 High groundwater flux generated quick temperature stabilization. When  
407 the Darcy velocity was too high ( $> 2.0 \times 10^{-5} \text{ m s}^{-1}$ ), the sampling time of the  
408 experiments was unsuited to visualize the linear part of the thermal evolution  
409 plot (an example is provided in Figure 8d). Consequently, thermal conductiv-  
410 ity  $\lambda$  could not be estimated properly and was fixed at  $2.8 \text{ W m}^{-1} \text{ K}^{-1}$ . This  
411 value corresponds to an average value for limestone rocks [Dalla Santa et al.,  
412 2020]. Further discussion about the impact of  $\lambda$  values on the estimated  $q$   
413 value is given in subsection 5.2.

414 The analytical models had a good fit to the field data, ,with the value of

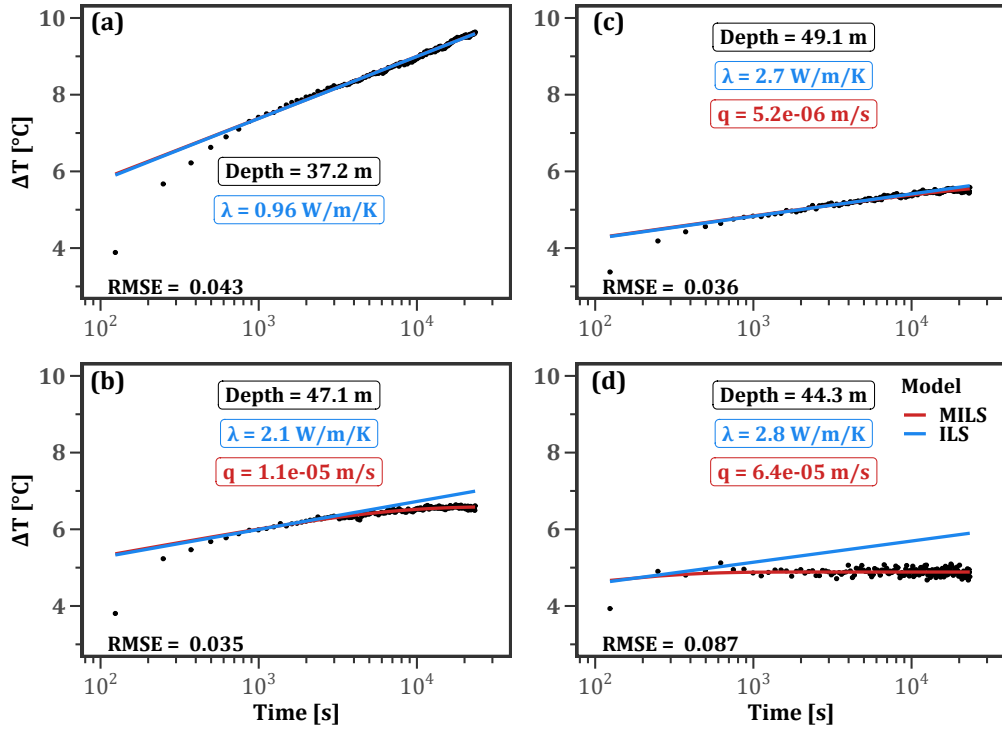


Figure 8: Determination of mean thermal conductivity  $\lambda$  and Darcy velocity  $q$  (piezometer Pz51) when, (a) only conduction occurs, (b) low flux is detected, (c) medium flux and (d) high flux occur with an early temperature stabilization due to higher groundwater flow.

415 the Root Mean Square Error (RMSE) generally remaining low, i.e.  $RMSE <$   
 416  $0.1$ . The maximum value of  $0.15$  was calculated for the high Darcy velocity  
 417 interval.

418 Low  $q$  values below  $3.0 \times 10^{-6} \text{ m s}^{-1}$  should be considered cautiously. It was  
 419 demonstrated that an experimental time of 24h with an error of  $\pm 0.05 \text{ }^\circ\text{C}$  on  
 420 the field temperature measurement, lead to errors above 20% on  $q$  estimation  
 421 [Simon et al., 2021]. This error grew exponentially with the decrease of  
 422 estimated  $q$ .

423 *4.2.3. Groundwater and thermal conductivity distribution*

424 Vertical distribution of  $\lambda$  and  $q$  were computed for each sampling depth  
425 along the two branches of the U cable (Figure 9). In each piezometer, the  
426 2 branches gave similar parameter estimations, suggesting the consistency  
427 of the data acquisition and its processing. The uncertain  $q$  values below  
428  $3.0 \times 10^{-6} \text{ m s}^{-1}$  were represented in a shaded area on the corresponding  
429 profiles (Figure 9a and c).

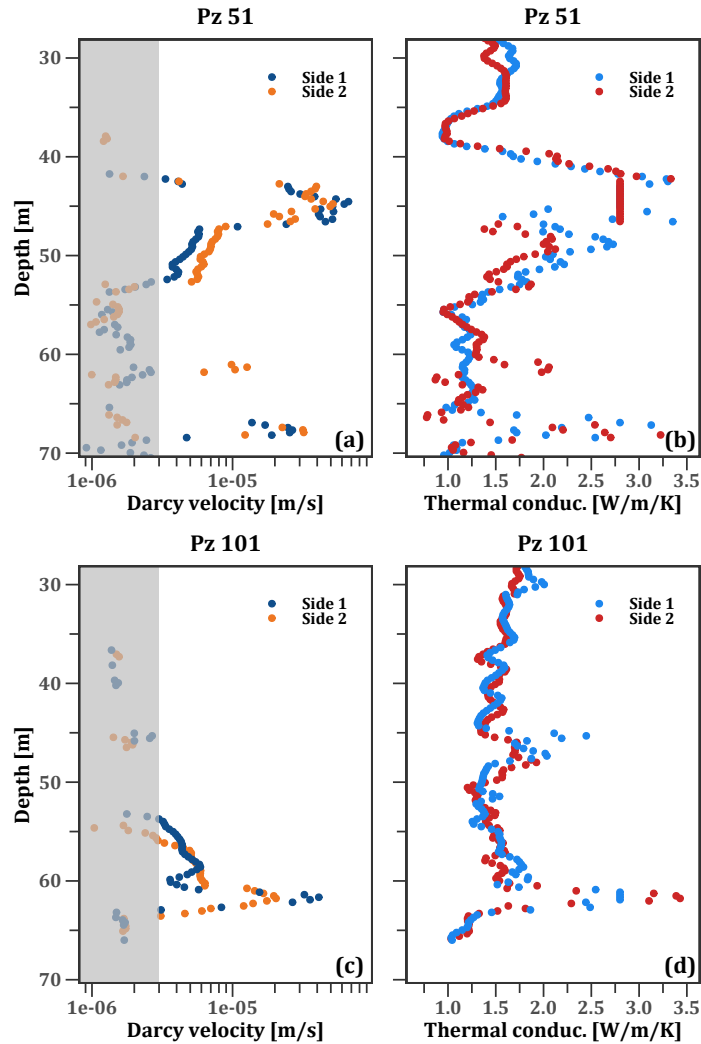


Figure 9: Parameter profiles estimated from FO-ADTS experiments in front of screened areas : (a and c) groundwater flux profiles, shaded areas correspond to estimated values with high uncertainty, (b and d) thermal conductivity profiles

430 Despite the short distance between Pz101 and Pz51 (8.5 m), the esti-  
 431 mated  $q$  profiles showed major discrepancies in front of the borehole screens.  
 432 These  $q$  profiles were not equally distributed along the flowing areas of both

433 piezometers, highlighting a reciprocity gap. In Pz51, high Darcy velocities  
434 of  $5.0 \times 10^{-5} \text{ m s}^{-1}$  were estimated in the intervals of 43–46 m and 67–68 m  
435 (Figure 9a). A lower peak of  $1.0 \times 10^{-5} \text{ m s}^{-1}$  was detected in one branch at  
436 the depth of 62 m. From the depth of 46 m to 53 m, the  $q$  value decreased  
437 from  $7.0 \times 10^{-6} \text{ m s}^{-1}$  to  $4.0 \times 10^{-6} \text{ m s}^{-1}$ . As for Pz101, the ADTS experi-  
438 ment allowed to estimate a high Darcy velocity superior of  $2.0 \times 10^{-5} \text{ m s}^{-1}$   
439 only in the thin layer at the depth of 62 m. A medium flow of an aver-  
440 age of  $5.0 \times 10^{-6} \text{ m s}^{-1}$  was estimated between the length interval 54–61 m  
441 (Figure 9c).

442 In front of the screens, the low  $\lambda$  values were always estimated in front of  
443 no- or low flux areas. In Pz51, a value close to  $1.0 \text{ W m}^{-1} \text{ K}^{-1}$  was estimated  
444 in the length intervals 35–39 m and 54–67 m. On the contrary, high  $\lambda$  values  
445 were calculated where significant  $q$  values were calculated. This trend was  
446 also detected in Pz101. High  $\lambda$  values of  $3.0 \text{ W m}^{-1} \text{ K}^{-1}$  were measured in  
447 front of the highest Darcy velocity area at the depth of 62 m, whereas the  
448 values fluctuated around  $1.5 \text{ W m}^{-1} \text{ K}^{-1}$  in the rest of the piezometer.

## 449 5. Discussion

### 450 5.1. Consistency of the ADTS results in relation with available field data

451 The parameters profiles obtained from ADTS experiments were compared  
452 to available independent field data. The  $q$  profile in Pz51 emphasized the  
453 same high productive layer as the one detected in the GF1 flowmeter log at  
454 the depth of 44–46 m. The Darcy velocity reached a value of  $5.0 \times 10^{-5} \text{ m s}^{-1}$

455 at this depth. Nevertheless, the flowmeter log achieved one year after bore-  
 456 hole completion in Pz101 suggested a homogeneous flux distribution probably  
 457 influenced by the clogging development along this borehole. But, the ADTS  
 458 detected a medium Darcy velocity of  $5.0 \times 10^{-6} \text{ m s}^{-1}$  where the screens are  
 459 just partially clogged below the depth of 53 m.

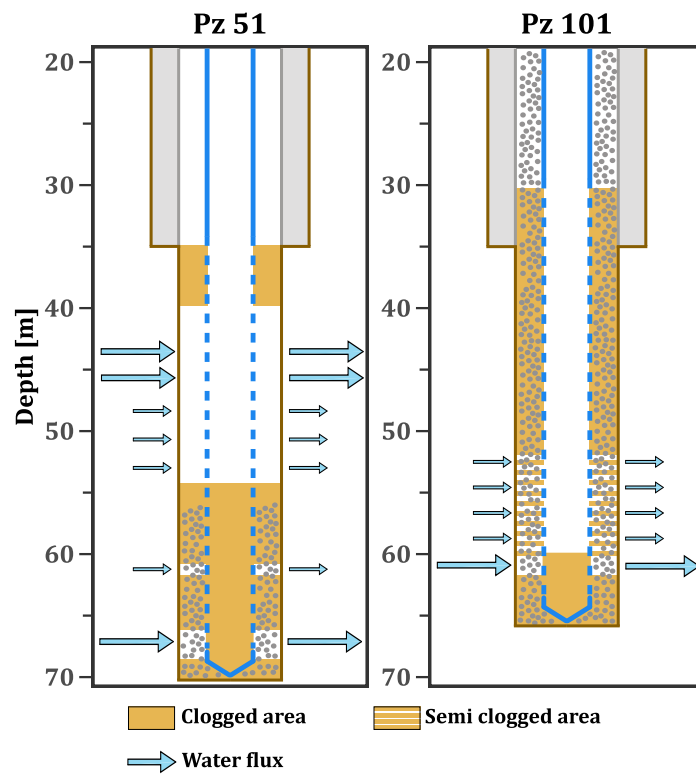


Figure 10: Interpretation scheme of boreholes clogging and flux location according to video inspection, parameters distribution and injection flow paths

460 In both piezometers, weak or zero Darcy velocity values were measured  
 461 in front of clogged layers detected during video inspection (Figure 2f, g,  
 462 and h). The  $\lambda$  values of these layers were always inferior to  $1.5 \text{ W m}^{-1} \text{ K}$

463 (Figure 9b and d). It is typical for clogging materials like clay, bentonite  
464 and porous iron hydroxides [Dalla Santa et al., 2020, Cho et al., 2008, Tang  
465 et al., 2008, Gjengedal et al., 2020] and does not correspond to the typical  
466 values of the thermal conductivity of the limestone, i.e.  $3.0 \text{ W m}^{-1} \text{ K}$ . These  
467 observations highlight the potential of ADTS experiments to locate zones of  
468 borehole clogging. We believe that the main reason for the clogging is related  
469 to the fact that these wells were planned only for monitoring purpose, and,  
470 as a consequence, were not sufficiently developed after their completion. The  
471 clogged materials did not have the same position along both boreholes .It  
472 seems to be the main explanation for reciprocity gaps between parameters  
473 distribution in Pz51 and Pz101. The drill cuttings assessment revealed the  
474 same geology in both boreholes. But, a fracture or a more productive area  
475 might be intercepted in Pz51 and GF1 and not in Pz101 and could be the  
476 reason of a high flux in Pz51 and GF1, involving the dilution of the bentonite  
477 in Pz51 and not in Pz101.

478 The video camera showed bentonite and clay at the bottom of both  
479 piezometers. The position of the plugs, at the depth of 54.5 m in Pz51  
480 and 60 m in Pz101, corresponded exactly to the limits highlighted by Exper-  
481 iment 2 and Experiment 4 (Figure 6). It confirmed that during injection, the  
482 water did not flow in the lower part of the piezometers. Nevertheless, during  
483 Experience 1 and Experience 3, some fluxes were detected below the well  
484 bottoms, at the depths of 62 m in Pz101 and 62 m and 68 m in Pz51 (Fig-  
485 ure 10). It may point out that at these depths, the boreholes were clogged

486 but the deposits were not completely compacted/encrusted into the annular  
487 space. High thermal conductivity values ( $> 3.0 \text{ W m}^{-1} \text{ K}^{-1}$ ) may confirm a  
488 likely dilution of the mud in these intervals.

### 489 5.2. Uncertainty and resolution of parameters calculation

490 In highly productive layers, the groundwater flow generated a fast tem-  
491 perature stabilization. In this context, ADTS experiments with a sampling  
492 time of more than 1 minute are unsuited to visualize the linear part of the  
493  $\Delta T_{exp}$  plot before the temperature stabilization (Figure 8d). Consequently,  
494 it is not possible to accurately estimate the thermal conductivity  $\lambda$ . Con-  
495 sequently, values of thermal conductivity consistent with the properties of  
496 the porous material [Dalla Santa et al., 2020] encountered in the borehole  
497 must be chosen as the default value. However, in high productive context,  
498 it is possible to demonstrate the low impact of  $\lambda$  on the estimated Darcy  
499 velocity (Figure 11). A sampling time of a few seconds would be necessary  
500 to visualize the conductive phase in this context. Nevertheless, a short sam-  
501 pling time produce noisier data which can also lead to high uncertainty [des  
502 Tombe et al., 2020].

503 As mentioned in section 4.2.1, the analytical model used in this study  
504 ignored thermal dispersion. By doing this, the thermal diffusivity is over-  
505 estimated. It could be another source of error that could lead to under-  
506 estimating  $q$ , especially in high-flow areas. It was demonstrated that an  
507 estimated  $q$  of  $5.0 \times 10^{-6} \text{ m s}^{-1}$  without considering the thermal dispersion

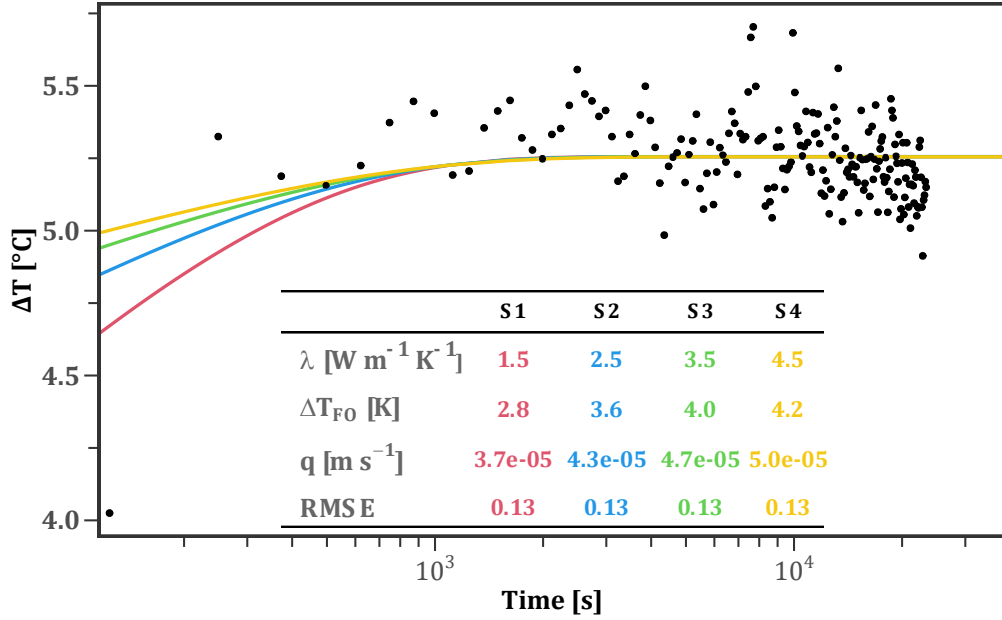


Figure 11: Analytical solutions generated from the framework to reproduce experimental temperature evolution at 45.2m in Pz51 with a large scale of  $\lambda$  from 1.5 to 4.5  $\text{W m}^{-1} \text{K}^{-1}$

508 will yield a  $q$  of  $9.0 \times 10^{-6} \text{ m s}^{-1}$  if the longitudinal dispersivity is set at 0.1  
 509 m [des Tombe et al., 2019]. Nevertheless, in our experiment, the effect of  
 510 thermal dispersion should be very small, if not negligible, since here, we use  
 511 the same cable as a heat source and for measuring temperature.

512 Moreover, the vertical resolution of the DTS is a limit to measure temper-  
 513 ature variations induced by layers with a thickness ranging this resolution.  
 514 Even if a thin layer is detected by the FO DTS experiment, the measured  
 515 temperature in front of this layer is a result of the surrounding conditions  
 516 leading to uncertainty in parameter estimation [des Tombe et al., 2019, Simon  
 517 et al., 2020].

518 Finally, parameters estimation, especially  $\lambda$  estimation, is influenced by  
519 the test configuration. The resolved parameters are unlikely to provide the  
520 true aquifer properties since the FO cable is located in the borehole annu-  
521 lar space, close to the PVC tube, surrounded by the gravel and clogging  
522 material. Despite these uncertainties, one should rather focus on relative pa-  
523 rameter variation to identify clogging locations and productive layers along  
524 the borehole.

### 525 *5.3. Advantages and limits of the proposed ADTS experiments*

#### 526 *5.3.1. Comparison with common field surveys*

527 These experiments demonstrated that ADTS could provide in short time  
528 information regarding two crucial concerns for ATES operation: (i) the  
529 method provides important insights regarding the aquifer heterogeneity in  
530 thermal and hydrodynamic properties and (ii) it enables the detection of  
531 clogging locations in the borehole. ADTS experiment presents the advan-  
532 tage to estimate a distribution of parameters while pumping tests and TRT  
533 give an average value of hydrodynamics and thermal properties. Moreover,  
534 these surveys require much longer time of data collection (i.e., at least 48h  
535 versus 4-6 h required for the completion of ADTS tests). However, TRT and  
536 pumping tests are very simple to deploy, and their well-known and relatively  
537 quick interpretation can give a first overview of the global aquifer dynamics.

538 Unlike ADTS, flowmeter tests are not designed to provide information  
539 about conductive heat transfers which could be of great interest in geothermal

540 projects. Nevertheless, the single-hole flowmeter is a common survey that  
541 can be achieved in a shorter time than ADTS, after a borehole completion.  
542 It has also the advantage of a more simple setup than the ADTS one. It  
543 provides a local vertical distribution of the fluxes at the logging well, and is  
544 used to estimate permeability variations along the aquifer [Molz et al., 1989,  
545 1994, Paillet, 1998]. The application of the flowmeter test in cross-borehole  
546 configuration proved to be also an efficient methodology to have a better  
547 characterization of aquifer dynamics at a large scale. It allows highlighting  
548 connectivity of preferential groundwater flow paths [Le Borgne et al., 2006a,b,  
549 Audouin and Bodin, 2008].

550 The ADTS experiments give thermal conductivity only in the vicinity  
551 of the monitoring well. To characterize aquifer heterogeneity and thermal  
552 diffusivity on large scales, heat tracer tests with multiple monitoring well  
553 may be more powerful experimental field test [Klepikova et al., 2016]. It  
554 provides additional information compared to solute tracer tests, since the  
555 thermal diffusivity is higher than the solute dispersion [Irvine et al., 2015,  
556 La Bernardie et al., 2018]. Consequently, heat tracer tests are more suited for  
557 geothermal sites. However, due to the ability of heat to propagate through  
558 solids by diffusion, completion of heat tracer tests may take much longer  
559 time compared to solute tracer tests (days vs hours).[Irvine et al., 2015,  
560 La Bernardie et al., 2018]. It can also be difficult to realize and interpret  
561 compared to ADTS experiments.

562 .

563       Recent studies [Gjengedal et al., 2020, 2021] based on short step-test com-  
564 bined with temperature and hydraulic performance monitoring, first demon-  
565 strated a new technique enabling the detection of clogging and its further  
566 evolution characterization in geothermal systems. While this method allows  
567 the detection of clogging in the entire system, it does not precise the clogging  
568 location in the boreholes. The new characteristic of our ADTS interpretation  
569 is to image clogging distribution in the monitoring well. Therefore, this new  
570 strategy and the one proposed by Gjengedal et al. [2020] could complement  
571 each other. Once deployed in the borehole, and all cable connections realized,  
572 ADTS technology could be used as a permanent *in-situ* device. It presents  
573 a certain advantage as it can collect a large amount of data without opening  
574 the borehole and removing the submersible pump. The aim would be to  
575 monitor clogging evolution and aquifer properties changes over time and to  
576 plan and adapt maintenance works before major deterioration of the wells.  
577 This aspect would be time and financial saving compared to diagnostic well  
578 works, or video camera inspections to visualize clogging development. It is  
579 also an advantage to have a permanent fiber in the borehole. It allows to  
580 warm the cable and collect the data with the DTS unit without deploying the  
581 fiber in the borehole before each experiment like the methodology proposed  
582 by Maldaner et al. [2019].

583 *5.3.2. Potential limits of cross-borehole ADTS experiments in a geothermal*  
584 *operational context*

585 Our experiments were achieved in wells made of PVC tubes and screens.  
586 This material has a low thermal conductivity of  $0.2 \text{ W m}^{-1} \text{ K}^{-1}$ . It gives a  
587 limited impact on the temperature evolution generated by the warming of the  
588 fiber. This impact was included in the skin effect during our interpretation  
589 process. Nevertheless, a lot of wells are made of steel or stainless steel. Be-  
590 cause of the high thermal conductivity of this material ( $15\text{-}30 \text{ W m}^{-1} \text{ K}^{-1}$ ),  
591 the energy demand may be significant to create a temperature increase de-  
592 tectable by the DTS device. A numerical model taking into account a well  
593 equipped with steel material would be necessary to inspect the feasibility of  
594 ADTS experiment in this configuration.

595 While on the ENSEGID site, the exploited aquifer is found at a shallow  
596 depth (35-65 m), in other sites, the geothermal target may be deeper. The  
597 longer cable length required for deeper applications will generate an addi-  
598 tional economic cost, and the deployment of the technology in the borehole  
599 will be more time-consuming. Moreover, longer heated section of the cable  
600 will require more power injection to reach similar temperature variations. In  
601 this context, it is a major concern to provide suitable devices able to inject  
602 safely more electrical power.

603 Finally, the ENSEGID site is equipped with several wells close to each  
604 other, thus offering a good opportunity to perform ADTS experiments in  
605 cross-borehole configuration. Monitoring and pumping boreholes are only

606 separated by a distance of 8.5 m and a flowrate inferior to  $5.0\text{ m}^3\text{ h}^{-1}$  was  
607 enough to induce groundwater flux measurable by the ADTS experiment.  
608 Nevertheless, on geothermal sites just equipped with a warm and a cold well,  
609 the high distance (generally more than 100 meters) between the wells to  
610 avoid thermal breakthrough, may be a limit to perform cross-borehole ADTS  
611 experiments. Depending on the hydrogeological context and the capacity of  
612 the installed submersible pump, the groundwater velocity at the monitoring  
613 well may not be detectable by the presented ADTS experiment configuration  
614 and interpretation scheme. In this case, a single-hole ADTS configuration,  
615 like the one proposed by Read et al. [2014], may be more suited.

## 616 **6. Conclusion**

617 This study demonstrated the potential of ADTS experiments to collect  
618 and interpret a large amount of data by placing a FO between the borehole  
619 screens and the porous media. Our study allowed to characterize simultane-  
620 ously the distribution of thermal conductivity and Darcy velocity in a short  
621 time (4-6 hours per experiment), and to get useful insights about the water  
622 injection pathways in boreholes. Moreover, the data provided information  
623 concerning the position of the clogging development along the screens.

624 In the future, it would be certainly of interest to test ADTS experiments  
625 on a new operational geothermal site. The aim would be to determine initial  
626 parameters profiles before the beginning of ATEs operation in the produc-  
627 tion/injection wells, and then, monitor their evolution during a long-term

628 operation to have an overview on the wells performance behavior.

629

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