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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

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

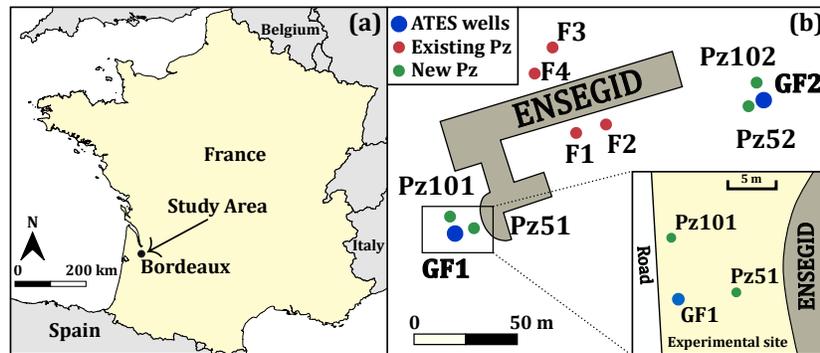


Figure 1: (a) Location of experimental area, (b) ENSEGID site map with boreholes location and focus on the experimental area

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 Géosources 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 m². 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.

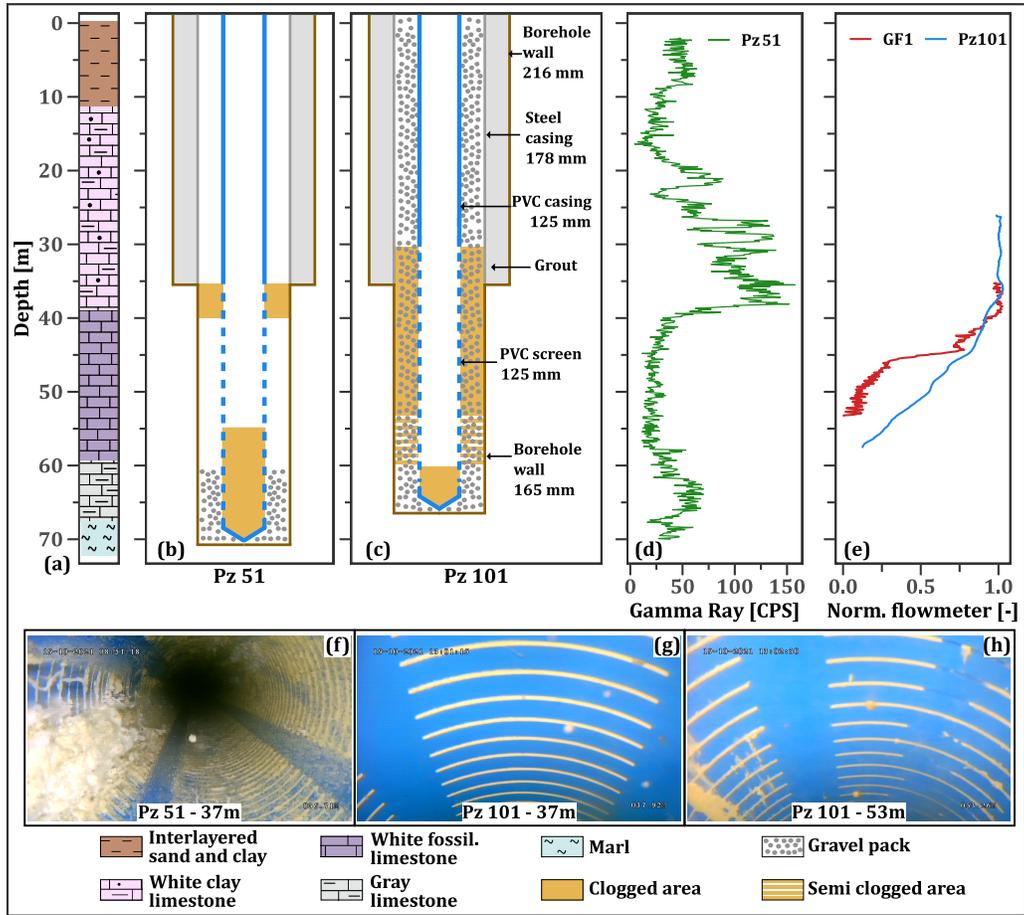


Figure 2: Field data : (a) Geological section of the site, (b) and (c) technical logs of piezometers with clogged area detect during video inspection, (d) Pz51 gamma ray, (e) GF1 and Pz101 flowmeter logs, and (f,g,h) video inspection screenshots

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.

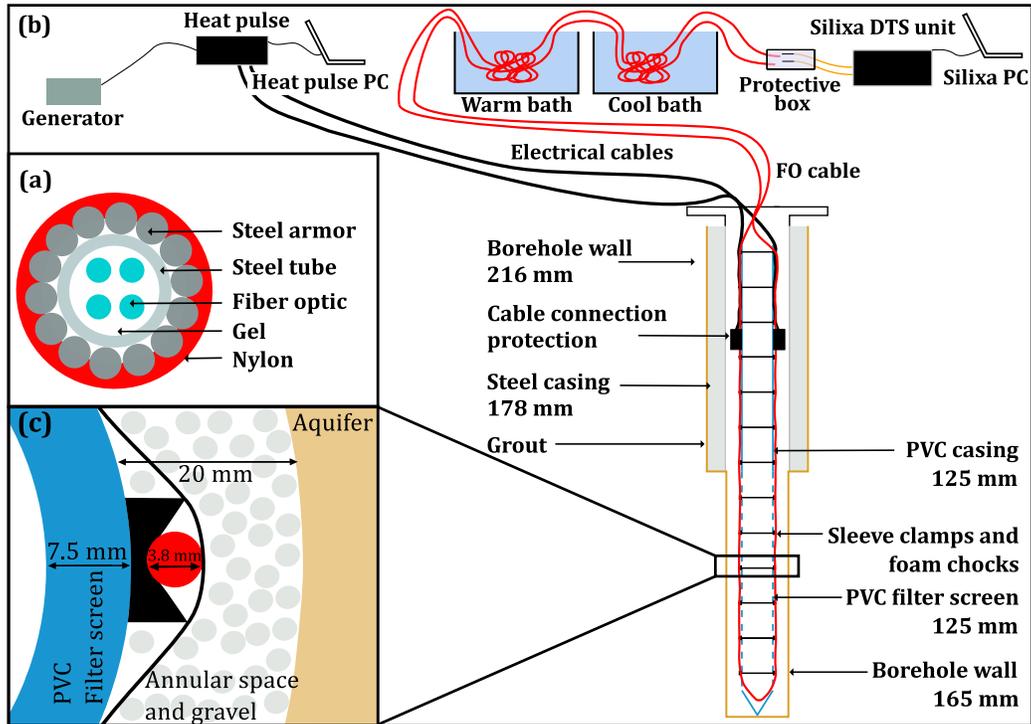


Figure 3: Device installation scheme : (a) transverse section of the FO cable, (b) scheme of experimental configuration with acquisition well and FO-DTS set up, (c) traverse borehole section representing fiber configuration in annular space

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.

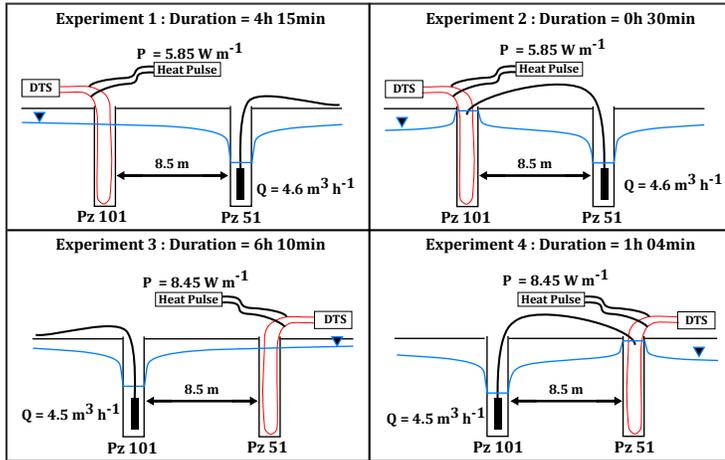


Figure 4: Scheme of the four experiment configurations with the indicated injected power by the heat pulse P and the pumping rate Q .

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°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.

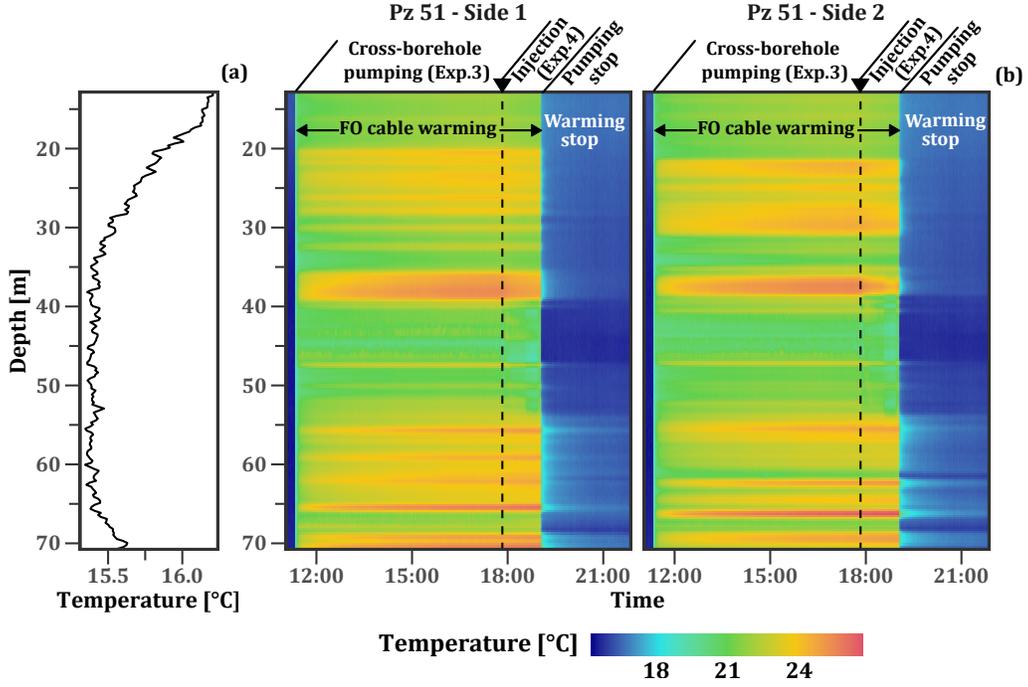


Figure 5: Temperature distribution along the FO cable in Pz51: (a) natural *in-situ* profile before the heating and (b) temperature variation with both time and depth along the two side of the FO loop. The temperatures measured at each side of the U cable are similar

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 ΔT_{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 ΔT_{inj} profiles revealed three
 314 different zones in both piezometers (Figure 6a and c).

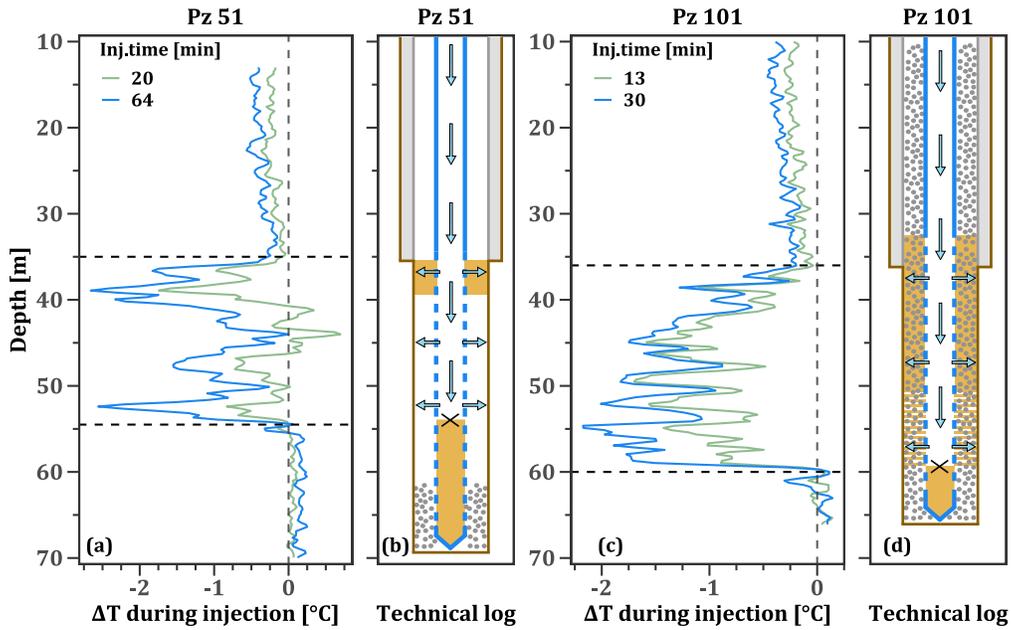


Figure 6: Experimental injection results : (a) and (c) relative temperature anomaly profiles ΔT_{inj} at different times since the beginning of the injection; (b) and (d) technical log with identified clogged area from video inspection and flux pathway deduced from injection experiment represented by 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°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 ΔT_{inj} of -2.0°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 λ 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 [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 λ 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 ΔT is the temperature evolution, P [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]. λ 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

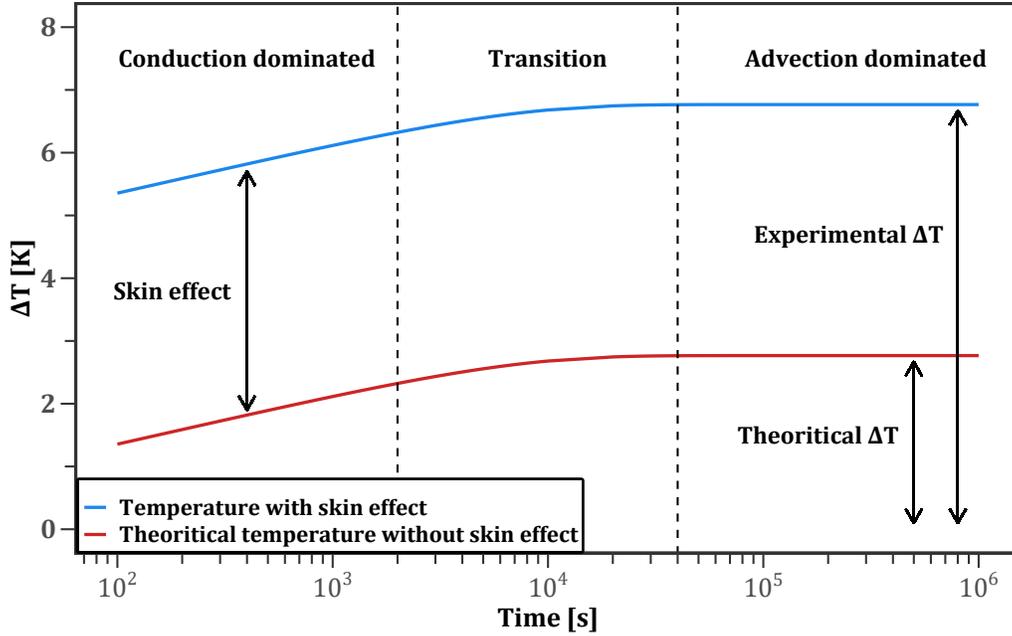


Figure 7: Theoretical temperature evolution in response to a heat pulse in saturated porous media with and without skin effect of the FO cable (adapted from [del Val et al., 2021])

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 ΔT_{exp} measured by FO-DTS. This
 385 difference was taken into account in a ΔT_{FO} term (Figure 7). Thus, to model
 386 the temperature increase during the experiment, ΔT_{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 λ 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 λ 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 λ . Advection transfer generated a transition phase until temperature
404 stabilization (Figure 8b and c), and both analytical solutions were used to
405 estimate λ 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 λ 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 λ 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

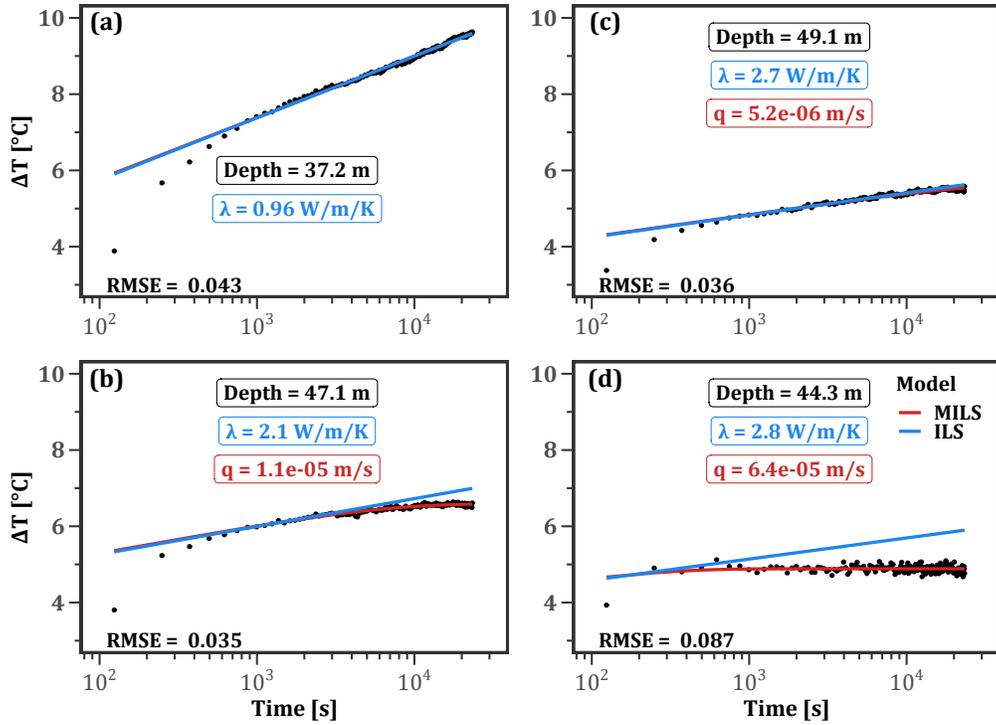


Figure 8: Determination of mean thermal conductivity λ and Darcy velocity q (piezometer Pz51) when, (a) only conduction occurs, (b) low flux is detected, (c) medium flux and (d) high flux occur with an early temperature stabilization due to higher groundwater flow.

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 λ 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).

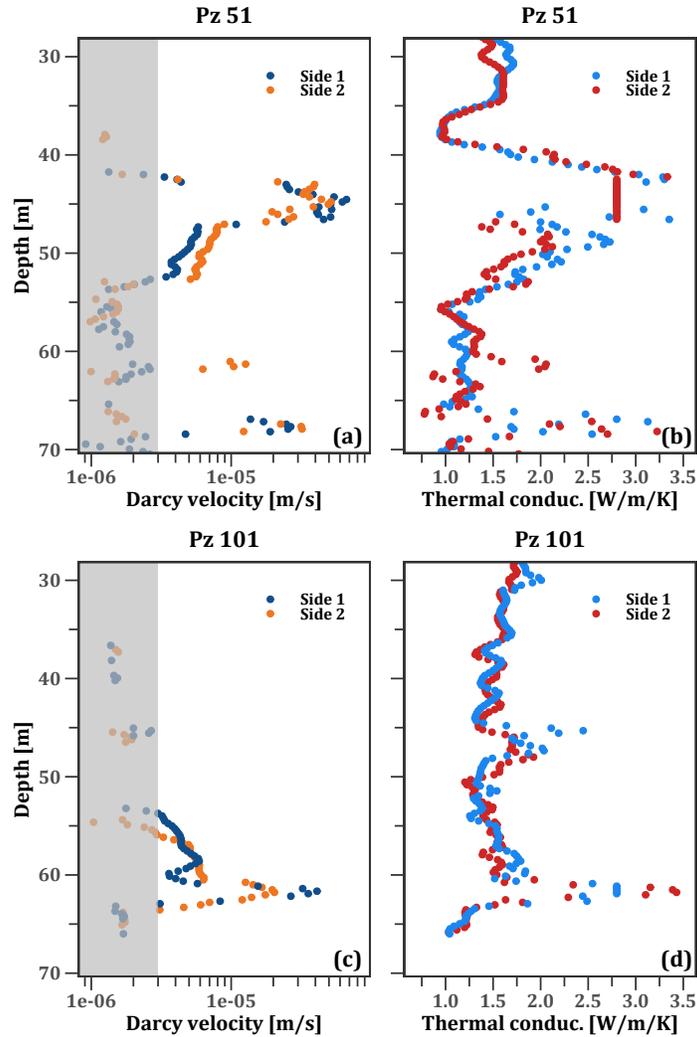


Figure 9: Parameter profiles estimated from FO-ADTS experiments in front of screened areas : (a and c) groundwater flux profiles, shaded areas correspond to estimated values with high uncertainty, (b and d) thermal conductivity profiles

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 λ 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 λ values
445 were calculated where significant q values were calculated. This trend was
446 also detected in Pz101. High λ 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.

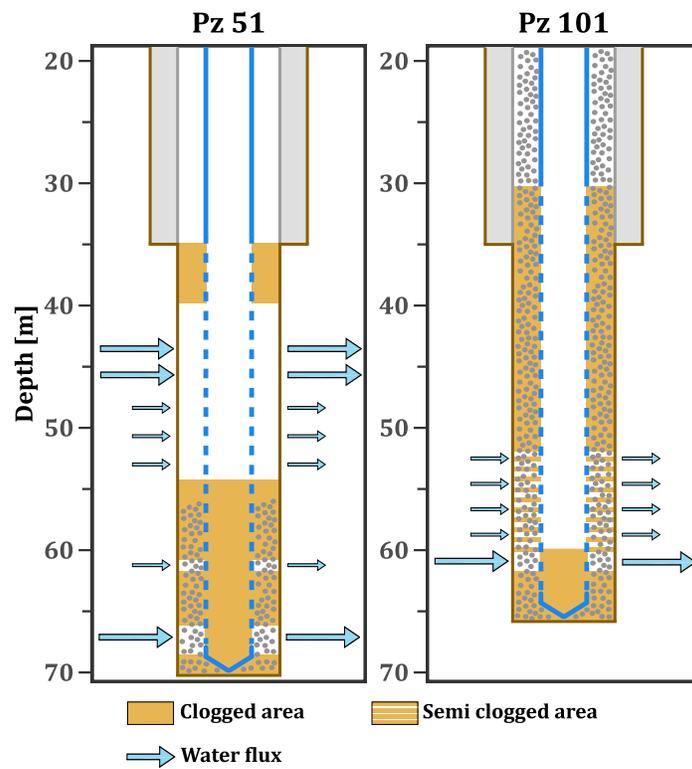


Figure 10: Interpretation scheme of boreholes clogging and flux location according to video inspection, parameters distribution and injection flow paths

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 λ 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 ΔT_{exp} plot before the temperature stabilization (Figure 8d). Consequently,
494 it is not possible to accurately estimate the thermal conductivity λ . 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 λ 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

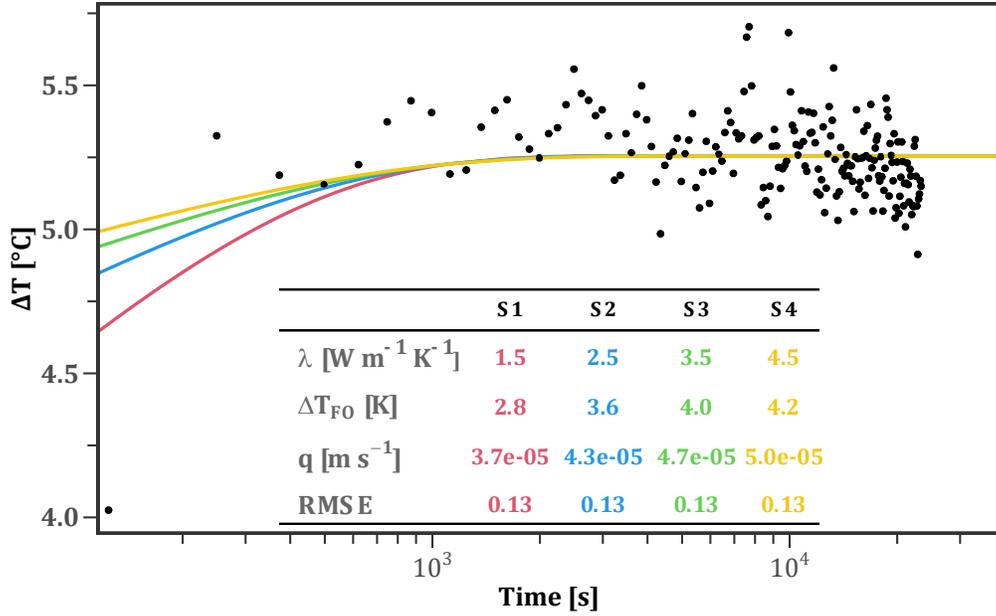


Figure 11: Analytical solutions generated from the framework to reproduce experimental temperature evolution at 45.2m in Pz51 with a large scale of λ from 1.5 to 4.5 $\text{W m}^{-1} \text{K}^{-1}$

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 λ 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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