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Groundwater flow characterization of an ophiolitic hard-rock aquifer from cross-borehole multi-level hydraulic experiments

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Abstract

Ophiolitic formations play a critical role in the groundwater resource of numerous countries and areas. Previous studies show that the structural heterogeneities of these rocks, coming from the presence of both different lithological units and multi-scale discontinuities, result in complex hydrogeological features that are not well characterized yet. In particular, there is a need for understanding how these heterogeneities impact the hydrodynamic properties of ophiolitic aquifers and the highly variable chemical composition of the water. To this end, we conduct various kinds of pumping experiments between two boreholes 15 m apart in the ophiolitic formation of the Batin (BA1) site in the wadi Tayin massif of the Sultanate of Oman. Cross-borehole open pumping experiments, as well as multi-level pumping and monitoring hydraulic tests, are performed in conductive zones that were identified from temperature and flowmeter data, but also in low-permeability zones requiring

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to manage very low pumping flow rates. The collected data are interpreted with a model implementing non-integral flow dimension, leakage and time-dependent pumping flow rates. The considered modeling concepts and the estimated hydrogeological properties show that the multi-directional structural heterogeneities of ophiolitic aquifers are key features that must be considered in future hydrogeological models because they drive the hydraulic responses of these systems.

Keywords: Ophiolitic aquifer, Cross-borehole hydraulic test, Multi-level packer pumping experiment, Heterogeneous hydrosystems, Hydraulic property estimation, Variable flow-rate model

1. Introduction

Ophiolitic rocks are fragments of oceanic crust and upper mantle which are widespread on the surface of continents along tectonic suture zones (e.g., Abbate et al., 1985; Boronina et al., 2005; Maury and Balaji, 2014; Segadelli et al., 2017b; Vacquand et al., 2018; Jeanpert et al., 2019). These rocks extend from the Alps to the Himalayas through, for instance, Cyprus, Syria and Oman, and are also present in various countries such as Cuba, USA, Papua-New Guinea, New Caledonia and Newfoundland (Abbate et al., 1985). Ophiolites are important groundwater resources in some areas (e.g., within the northern Apennines (Segadelli et al., 2017b) and in Cyprus (Boronina et al., 2005)). In Oman, ophiolite water was a key resource for the population that started in 3000 BC. Nowadays, the main fresh water supply in the towns bordering the Oman gulf including Muscat comes from sea water desalinisation, but ophiolites still provide the only source of water for

15 agriculture (including dates growing, which is often the main income for vil-
16 lagers) in several inland areas where people built underground galleries called
17 Aflaj (plural of Falaj) for irrigation since 5000 years. Villages developed close
18 to the (often intermittent) rivers (wadis) that form from the ophiolite wa-
19 ter sources often occurring at the peridotite - gabbro interface, the former
20 forming the low permeability reservoir while the latter, fractured and often
21 altered, draining the ophiolite massif water toward sources (Dewandel et al.,
22 2004). In a general manner, ophiolites may impact strongly the chemical
23 composition of the water (e.g., in western Serbia (Nikic et al., 2013) and
24 Oman (Paukert-Vankeuren et al., 2019)) because of the high reactivity of
25 the rock-forming minerals which makes some water sources unsuitable for
26 human use. Ophiolites are composed of rocks such as basalt, dolerite, gab-
27 bro and peridotite, implying that they are characterized by the coexistence
28 of different lithological units, which can be fractured at many scales due
29 to cooling and (multiple) chemical alteration mechanisms. The presence of
30 structural discontinuities that control the permeability of these systems re-
31 sults in some similarities with the well-known and widely-studied fractured
32 granitic rock aquifers. However, these similarities in terms of fracturation do
33 not result in similar overall systems since the submarine conditions of for-
34 mation of ophiolitic rocks and weathering after exhumation lead to complex
35 hydrogeological properties that are not well characterized yet (e.g., Boron-
36 ina et al., 2003; Dewandel et al., 2005; Jeanpert et al., 2019). For instance,
37 at meter to tens of meters scales, far from faults, hydraulic discontinuities
38 in peridotites are often zones concentrating high density of fissures whereas
39 granite systems are usually homogeneous, poorly-permeable matrix hosting

40 pluri-meter scale, often sparsely distributed, discrete fractures.

41 The few studies conducted on ophiolitic aquifers show that the structural
42 heterogeneities of these systems, resulting from the presence of both different
43 lithological units and multi-scale hydraulic discontinuities (from fissure zones
44 to kilometer-scale faults), control their inherent behavior under ambient con-
45 ditions and their responses to forced conditions. As a result, the hydrogeo-
46 logical models that are built to understand and reproduce the hydrodynamic
47 of these aquifers are based on the coexistence of various recharge and trans-
48 missivity zones, which hydraulic properties depend on the lithological units
49 and discontinuities that are associated with the zones (e.g., Boronina et al.,
50 2003; Dewandel et al., 2005; Segadelli et al., 2017a). These properties are
51 estimated from different characterization techniques, including hydrograph
52 analysis, mercury porosity and hydraulic conductivity laboratory measure-
53 ments, as well as pumping tests (e.g., Boronina et al., 2003; Dewandel et al.,
54 2005; Jeanpert et al., 2019).

55 The large variety of existing techniques and possible configurations that
56 are associated with pumping experiments makes it a very useful tool for
57 characterizing the subsurface hydraulic properties. Conducting these ex-
58 periments in open boreholes, or using single or dual packers that are moved
59 along the boreholes, provide vertically-integrated or vertically-distributed hy-
60 draulic properties, respectively. The resulting changes in pressure are mon-
61 itored in either the pumped well (i.e., single-borehole experiments) or ob-
62 servation wells (i.e., cross-borehole experiments), which impacts the spatial
63 extent and meaning of the estimated properties (e.g., Bear, 1979; Le Borgne
64 et al., 2007; Day-Lewis et al., 2011). That being said, the quality of these

65 estimates depends on the models that are used to interpret the collected
66 hydraulic data. The line-source analytical solutions (e.g., Theis solution),
67 which are widely used because they are easy to implement, are well suited
68 for interpreting the intermediate and late-time responses that are collected
69 while applying steady pumping flow rates. However, the assumption of a
70 negligible effect of the pumped borehole storage might be critical when in-
71 terpreting early-time data related to transient pumping flow rates. Using
72 more sophisticated solutions, which take into account the wellbore storage
73 effect, the flow dimension related to the structural heterogeneities, and the
74 occurrence of leakage effects, leads to better estimates of the hydraulic prop-
75 erties of the studied systems, in particular when focusing on heterogeneous
76 systems and time-dependent pumping flow rates (e.g., Lods and Gouze, 2004;
77 Cihan et al., 2011; Yeh and Chang, 2013).

78 In the context of ophiolitic aquifers, only a few studies considered pump-
79 ing tests for characterizing these hydrosystems (e.g., Boronina et al., 2003;
80 Dewandel et al., 2005; Jeanpert et al., 2019). For the Kouris catchment in
81 Cyprus and the Koniambo massif in New Caledonia, hydraulic conductiv-
82 ity estimates were obtained from single-borehole pumping experiments and
83 packer tests, respectively, that are interpreted with simple analytical solu-
84 tions (Boronina et al., 2003; Jeanpert et al., 2019). For the ophiolite hard-
85 rock aquifers in Oman, the interpretation of open cross-borehole pumping
86 experiments with a dual-porosity (or dual-permeability) model led to esti-
87 mate the hydraulic conductivity and storage coefficients at various locations
88 (Dewandel et al., 2005). These studies emphasized that the efforts for char-
89 acterizing ophiolitic aquifers with pumping experiments need to be pushed

90 further by focusing on (i) conducting multi-level pumping experiments (i.e.,
91 packer tests) in order to obtain vertically-distributed estimates of the hy-
92 draulic properties, (ii) using sophisticated models for improving the quality
93 of the estimated properties, (iii) combining the complementary information
94 provided by open borehole experiments and packer tests where the packers
95 can be used for multi-level pumping and multi-level pressure monitoring, and
96 (iv) developing pumping techniques and specific equipment that are adapted
97 to low permeability zones with localized highly-permeable structures.

98 In this work, we address these challenges by conducting and analyzing
99 several kinds of pumping experiments in the ophiolitic Batin East site in
100 the Wadi Tayin massif of the Sultanate of Oman. To this end, we start by
101 analyzing open borehole pumping experiments that were conducted in two
102 boreholes (positioned 15 m apart), and we show that the considered systems
103 cannot be characterized with vertically-integrated hydraulic properties. In
104 order to infer vertically-distributed properties, we then consider multi-level
105 pumping experiments, as well as multi-level cross-borehole pressure monitor-
106 ing, with intervals defined from temperature and flowmeter data. In light
107 of direct geological observations and indirect data analysis, we consider non-
108 integral flow dimension models with vertical leakage that are used in the
109 context of time-dependent pumping flow rates. The corresponding results
110 show the complexity of the studied system for which both the lithological
111 units and discontinuities impact the estimated hydraulic properties in dif-
112 ferent proportions depending on the considered layer. In this work, we also
113 address the issue of pumping tests in poorly-permeable zones by present-
114 ing material, experimental methods and interpretation procedures especially

115 adapted to this challenge.

116 The site and methods are described in Section 2, the pumping experiments
117 and their interpretation are discussed in Section 3, and the results and general
118 conclusions are presented in Sections 4 and 5.

119 **2. Site and methods**

120 *2.1. Site description*

121 The International Continental Scientific Drilling Program (ICDP) Oman
122 Drilling Project (OmanDP) established a multi-borehole observatory in Wadi
123 Lawayni in the Wadi Tayin massif of the Samail ophiolite in 2018 to study
124 ongoing weathering processes, the associated hydrogeological system, and
125 the subsurface microbiome. Wadi Tayin massif is one of the largest and
126 most intact massifs within the Samail ophiolite. The observatory lies within
127 the mantle peridotite section, approximately 3 km north of the crust-mantle
128 transition zone (MTZ) in the south-eastern part of the massif (Figure 1). The
129 MTZ and surrounding crustal gabbroic and mantle rocks are displaced by sev-
130 eral kilometres along a set of NNW trending, strike-slip faults (e.g., Nicolas
131 et al., 2000). A prominent NNW trending fault system, with unknown sense
132 of displacement, cuts across Wadi Lawayni and the multi-borehole observa-
133 tory (Figure 1). The observatory consists of a multi-borehole array of drill
134 sites, including BA1, BA2A, BA3A and BA4A. Site BA1, which is the target
135 site for this study, includes one fully cored, 400 meter deep hole (BA1B) and
136 three rotary-drilled, 400 meter deep, 6-inch diameter holes (BA1A, BA1C
137 and BA1D) (Figure 2). Borehole BA1C collapsed at 60 meters depth shortly
138 after drilling and was abandoned. Based on core and drill cutting analysis,

139 the dominate lithologies in BA1A, BA1B, BA1C and BA1D are fully ser-
140 pentinized dunite in the upper 100 to 250 meters and partially serpentized
141 harzburgite in the deeper part of the boreholes. Preliminary analysis of bore-
142 hole wall images and the core from BA1B indicate high density of fractures
143 and veins, the majority of them sealed by carbonate or serpentine minerals.
144 Prior sampling and analysis of groundwater in a nearby government moni-
145 toring borehole (NSHQ-14), which is situated in the same catchment as the
146 observatory, reveal the occurrence of hyperalkaline (pH 11-12), $\text{Ca}(\text{OH})_2$ -rich
147 waters, which are the product of extensive water-rock interaction (e.g., Pauk-
148 ert et al., 2012; Miller et al., 2016; Rempfert et al., 2017; Paukert-Vankeuren
149 et al., 2019).

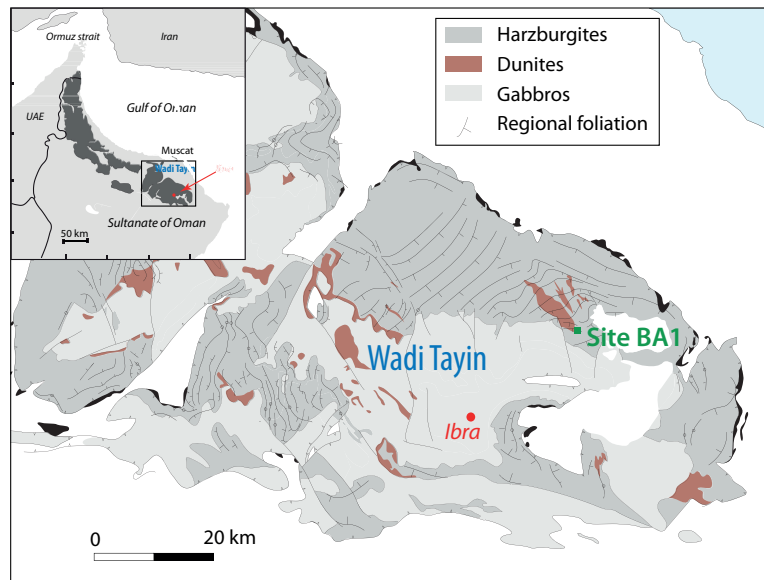


Figure 1: Map of the Wadi Tayin massif with the location of Site BA1 (modified after Noël et al. (2018), redrawn after Nicolas et al. (2000)). In inset, location of the Wadi Tayin massif in the Semail Ophiolite (North of Sultanate of Oman; redrawn after Einaudi et al. (2000)).

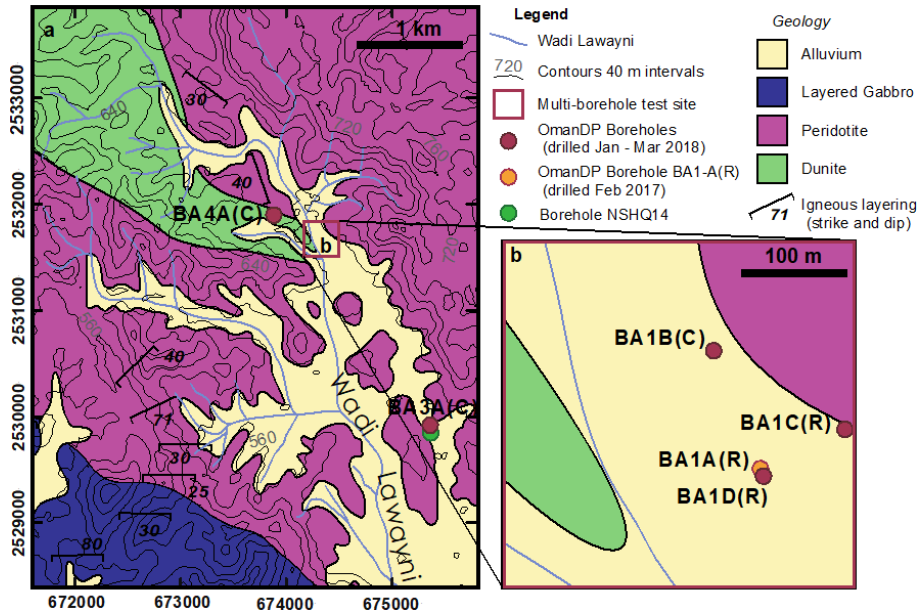


Figure 2: (a) Local geological map of Wadi Lawayni, Samail ophiolite (redrawn after Bailey (1981)). (b) Location of boreholes forming the BA1 multi-borehole observatory site.

150 *2.2. Material and method*

151 Figure 3 displays the schematic representation of the downhole part of
 152 the pumping system. It is installed from the surface using a tripod equipped
 153 with an electric chain hoist as a succession of individual parts of maximum
 154 3 m length that are assembled at the surface. From the bottom to the top,
 155 the dual-packer system includes:

- 156 - the lower pressure port (P_1) that measures the pressure below the lower
 157 packer;
- 158 - the lower packer. The two packers are 1 m long and can be inflated in-
 159 dividually so that one can perform single-packer or dual-packer pumping

- 160 test depending on the objectives;
- 161 - the pumping interval that can be set to a length ranging from 1 to 30 m;
 - 162 - the intermediary pressure port (P_2) that measures the pressure in the mea-
163 surement interval;
 - 164 - the upper packer;
 - 165 - the upper pressure port (P_3) that measures the pressure above the upper
166 packer. $P_3/\rho g$ measures the water column length above the upper packer,
167 ρ and g being the fluid density and gravitational acceleration, respectively;
 - 168 - the shut-in valve. When the packers are inflated, the valve is closed due to
169 the weight of all the equipment (pump and pipes) above it. It is opened
170 by pulling the pipe assemblage from the surface with the crane;
 - 171 - a stack of PVC pipe of length determined in order to position the pump
172 according to the depth of the upper packer and of the water table while
173 keeping a distance of 10 to 150 m below the water test static level (WTSL);
 - 174 - the pump (Grundfos SQE 1-140)

175 The downhole system displayed in Figure 3 is installed below the required
176 length of screwed PVC pipes of internal diameter 48 mm. The system is
177 linked to the surface by the electrical wire required for powering the downhole
178 pump as well as the data wire used to transmit the multiplexed data from
179 the pressure sensors (that also measure temperature) and the gas hoses for
180 inflating/deflating the packers that are included into a single cable. The
181 data including the pressure at the three measurement levels P_1 , P_2 and P_3
182 are recorded at the surface together with the two packer pressures and the
183 water flow rate measured by a flowmeter installed in-line at the well-head.

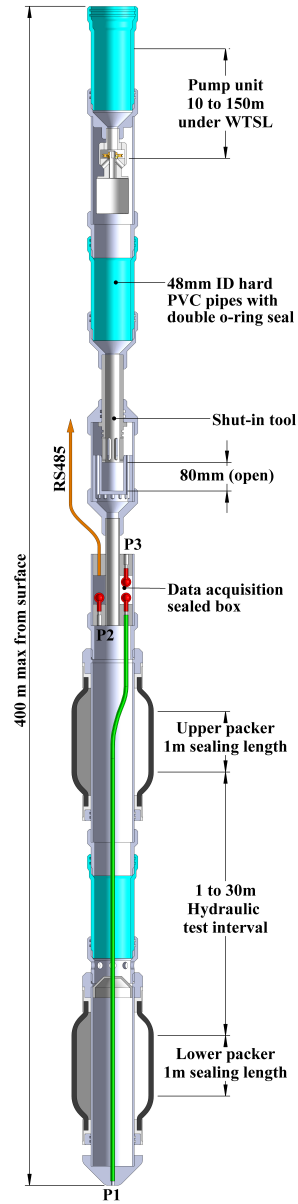


Figure 3: Schematic representation of the dual-packer system used for pumping tests.

184 *2.3. Experiments and models*

185 Three kinds of pumping experiments are considered for characterizing the
186 BA1 site presented in Section 2.1 with the material and method described in
187 Section 2.2. (i) Cross-borehole pumping tests are conducted with the pres-
188 sure being monitored in both (open) observation and pumped boreholes (Sec-
189 tion 3.1). These experiments are denoted *Exp1A* and *Exp1D* when pumping
190 in boreholes BA1A and BA1D, respectively. (ii) Multi-level pumping tests
191 are conducted by using packers in order to isolate and pump in specific in-
192 tervals of the pumped borehole while the pressure is monitored between the
193 packers (P_2), above the upper packer (P_3), and below the lower packer (P_1),
194 as well as in the (open) observation borehole. The intervals considered for
195 these experiments were determined from the analysis of profiles of tempera-
196 ture and flowmeter data, the latter profile being collected under ambient and
197 forced hydraulic conditions. This data are presented in Appendix A with
198 the pressures P_1 and P_3 that are monitored below and above the packers,
199 whereas pressure P_2 is analyzed in Section 3.2. The corresponding experi-
200 ments are denoted *Exp2A_i1A* and *Exp2A_i2A* when pumping is performed
201 in the intervals *i1A* (41-65 m) and *i2A* (108-132 m) of borehole BA1A, and
202 *Exp2D_i1D* and *Exp2D_i2D* when pumping is performed in the intervals *i1D*
203 (45-75 m) and *i2D* (102-132 m) of borehole BA1D. For both boreholes, we
204 also consider the zone below 132 m (i.e., 133-400 m), denoted *i3A* and *i3D*,
205 in order to characterize the low-conductivity zone that is located at the bot-
206 tom of the wells. The corresponding experiments are denoted *Exp2A_i3A*
207 and *Exp2D_i3D* when pumping in borehole BA1A and BA1D, respectively.
208 (iii) Finally, a cross-borehole multi-level-monitoring pumping experiment,

209 denoted *Exp3D* (Section 3.3), was conducted by using the packer system in
210 borehole BA1A while pumping in borehole BA1D with a Grundfos SQ2-85
211 pump. This test consisted in monitoring the pressure at several isolated po-
212 sitions in the observation borehole while the pressure is also monitored in
213 the (open) pumped borehole.

214 Table 1 summarizes the pumping and observation parameters of the ex-
215 periments by indicating in which borehole and at which position the pumping
216 and monitoring are done. 'Full' corresponds to open boreholes, whereas the
217 numbers indicate the distances in meter from the surface to the top and
218 bottom positions of the packers that are used to consider isolated intervals.
219 During all these experiments, the pressure was also monitored in borehole
220 BA1B (120 m NNW of BA1A and BA1D), in which no response was recorded.
221 This is likely due to the low permeability of the corresponding zone as shown
222 by the log data and core analysis of this borehole (not shown).

223 From a modeling point of view, the fractured nature of ophiolitic aquifers
224 leads to consider both dual-permeability and non-integral flow dimension
225 models, the former modeling concept being used in some previous studies
226 (Dewandel et al., 2005). Here, we focus on the latter conceptual models be-
227 cause of the following reasons: (i) Direct surface observations at the scale
228 of the test site showed numerous heterogeneously distributed centimeter to
229 decimeter-scale fractures but no large-scale hydraulic discontinuities such as
230 fractures that would have suggested the presence of two interconnected sys-
231 tems of distinctly different hydraulic properties, and as such should have
232 justified the use of dual-permeability models. (ii) The responses recorded
233 above and below the isolated intervals during packer tests with the pressures

	Pumping well		Observ. well	
	BA1A	BA1D	BA1A	BA1D
<i>Exp1A</i>	Full	-	-	Full
<i>Exp1D</i>	-	Full	Full	-
<i>Exp2A_i1A</i>	41-65	-	-	Full
<i>Exp2A_i2A</i>	108-132	-	-	Full
<i>Exp2A_i3A</i>	133-400	-	-	Full
<i>Exp2D_i1D</i>	-	45-75	Full	-
<i>Exp2D_i2D</i>	-	102-132	Full	-
<i>Exp2D_i3D</i>	-	133-400	Full	-
<i>Exp3D</i>	-	Full	22-107	-
			108-132	-
			133-400	-

Table 1: Setup at the pumping and observation boreholes for the set of hydraulic tests

²³⁴ P_1 and P_3 that are reported in Appendix A, show the presence of vertical
²³⁵ connections that can be modeled as vertical leakages in non-integral flow di-
²³⁶ mension models (Hamm and Bidaux, 1994). (iii) The results obtained in Sec-
²³⁷ tion 3 with non-integral flow dimension models are well in agreement with the
²³⁸ data and produce realistic estimations of the parameters and properties, thus
²³⁹ confirming that the use of more complex models (such as dual-permeability
²⁴⁰ models) is not necessary for the considered data. Dual-permeability models
²⁴¹ involve more parameters and as such more degrees of liberty that generally
²⁴² require making assumptions or using external data such as geophysical or
²⁴³ geological data. In the absence of such data that would have dictated using

244 dual-permeability models, the most parameter-parsimonious model must be
245 considered as the most probable model providing a fit to the data.

246 In order to interpret the data collected during these experiments, we
247 implemented a solution for transient radial flow in leaky aquifers with time-
248 dependent pumping flow rates using a fractal formalism. This representa-
249 tion is adapted to model hierarchical multi-scale fractured aquifers where
250 the characteristic length of the heterogeneity is smaller than the volume in-
251 vestigated by the pumping test (Lods and Gouze, 2008). We consider the
252 solution that is presented in Appendix B, which corresponds to an existing
253 solution for transient radial flow in a fractal fractured aquifer with leakance
254 that is extended to time-dependent pumping flow rates and non-linear skin
255 effects. From this solution, we derived four specific models corresponding
256 to (i) cylindrical flow without leakage (*Model1*), (ii) generalized radial flow
257 without leakage (*Model2*), (iii) cylindrical flow with leakage (*Model3*), and
258 (iv) generalized radial flow with leakage (*Model4*). The parameters that
259 distinguish these models from each other are summarized in Table 2. The
260 derivation of the models, the associated assumptions, and their use for in-
261 terpreting the data are given in Appendix C. The modeling strategy consists
262 in determining the model that best reproduces the values collected in both
263 the pumping and observation boreholes. When a common model cannot be
264 found, different models and parameters are considered for each borehole. We
265 select the best-fitting model by considering the quality of the overlap between
266 the curves of the simulated and collected data, as well as the physical meaning
267 of the estimated properties. For each experiment, the estimated parameters
268 of the models are presented in tables in which the parameters corresponding

269 to the selected best-fitting model are written in bold characters.

270 Finally, in order to have an independent estimate of the standard trans-
 271 missivity T (*Model1*), the transmissivity value estimated by interpreting the
 272 end of the recovery with Theis' method (Kruseman and de Ridder, 1990)
 273 is also provided. Since our models are based on unit-thickness aquifer rep-
 274 resentations for *Model1* (as explained in Appendix C), the estimated hy-
 275 draulic conductivity values of *Model1* are equivalent to transmissivity values
 276 and will be directly compared to the transmissivity estimated with Theis'
 277 method. The quality of the best-fitting models is also tested by estimating
 278 the drawdown in borehole BA1B, for which, as mentioned before, no response
 279 is observed during the pumping tests. The simulated values range from 0 to
 280 36.07 cm, showing in the latter case the impact of heterogeneities in hydraulic
 281 properties between the boreholes.

	Flow dimension	Leakage parameter
<i>Model1</i>	$N = 2$	$\beta = 0$
<i>Model2</i>	$1 \leq N \leq 3, N \neq 2$	$\beta = 0$
<i>Model3</i>	$N = 2$	$\beta > 0$
<i>Model4</i>	$1 \leq N \leq 3, N \neq 2$	$\beta > 0$

Table 2: Range of variations of the flow dimension (N) and leakage parameter (β) for the four models considered for data interpretation. $\beta = 1/B^2$ with B the leakage factor in Appendix B.

282 3. Experimental data and interpretation

283 3.1. Cross-borehole pumping tests

284 3.1.1. Pumping test in borehole BA1A

285 Figure 4 displays the data collected during the pumping experiment
286 *Exp1A* in the pumped and observation boreholes (black curve in Figures 4a
287 and b, respectively). In these figures, h is the difference in hydraulic head,
288 expressed in meter of water, between the beginning of the experiment ($t = 0$)
289 and time t . For technical reasons, h was not monitored in the pumped well
290 during the recovery period (Figure 4a). Figure 4c shows the pumping flow
291 rate monitored during the experiment (black curve), which was applied for
292 551 minutes with an average value of 44.9 L/min, and the flow rate mod-
293 eled with an exponential model (red dashed curve). The exponential model
294 is required for interpreting some of the experiments for which the flow rate
295 decreases noticeably. For this pumping test, the flow rate could have been
296 considered rightly as constant, but we applied the exponential model for mat-
297 ter of consistency. For this pumping test no common model reproducing the
298 data collected in both the pumped and observation boreholes could be found.
299 The models and parameters evaluated for each of the boreholes are given in
300 Table 3. Note that in this table, and in the rest of the manuscript, the values
301 of the skin factor (σ_w) and aquifer specific storage (S_s) that are estimated
302 from the pumped-borehole data are not shown because of their poor relia-
303 bility (Kruseman and de Ridder, 1990). However the variations of the skin
304 factor estimated from the pumped-borehole data are presented graphically
305 because their irregular variations reveal clogging/unclogging phenomena.

306 Concerning the data collected in the pumped borehole, *Model1* and *Model2*

307 provide an acceptable fit, which could not be improved with the leakage prop-
308 erties that are considered in *Model3* and *Model4* (Figure 4a). For *Model1*, it
309 is important to emphasize that additional simulations (not shown) demon-
310 strate that σ_w remains negative for $S_s < 1 \text{ m}^{-1}$, which indicates the presence
311 of open fractures that intersect the well (Ahmed and Meehan, 2011). The
312 presence of channelized flow in a fracture network is also indicated by the
313 flow dimension smaller than 2 for *Model2* (Le Borgne et al., 2004; Audouin
314 et al., 2008; Verbovšek, 2009). From the results presented in Figure 4a and
315 Table 3, this model is considered as the best-fitting model for the data col-
316 lected in the pumped borehole because it is the simplest model providing the
317 best fit to the data with the most realistic estimated parameters.

318 Different results are observed for the data collected in the observation
319 borehole. The transmissivity value estimated with *Model1* is consistent with
320 that of the standard Theis' method, which is equal to $1.27 \times 10^{-4} \text{ m}^2/\text{s}$. This
321 being said, *Model2*, *Model3* and *Model4* equally improve the fit between the
322 simulated and collected data in comparison with *Model1* (Figure 4b). In this
323 case, *Model2* is considered as the best fitting model because it is the simplest
324 model (in comparison with *Model4*) with the most realistic estimated value
325 of σ_w (in comparison with the large value of σ_w estimated with *Model3* and
326 shown in Table 3).

327 Finally, we wish to emphasize that defining a model for each borehole
328 presents the advantage of providing heterogeneous hydraulic properties be-
329 tween the pumped and observation boreholes. However, this implies that
330 some estimated parameters are weakly reliable and must be interpreted with
331 caution. This is the case for the skin factor σ_w that is estimated from the

332 adjustment done on the data collected in the observation borehole but is
 333 formally related to mechanisms occurring in the pumped borehole.

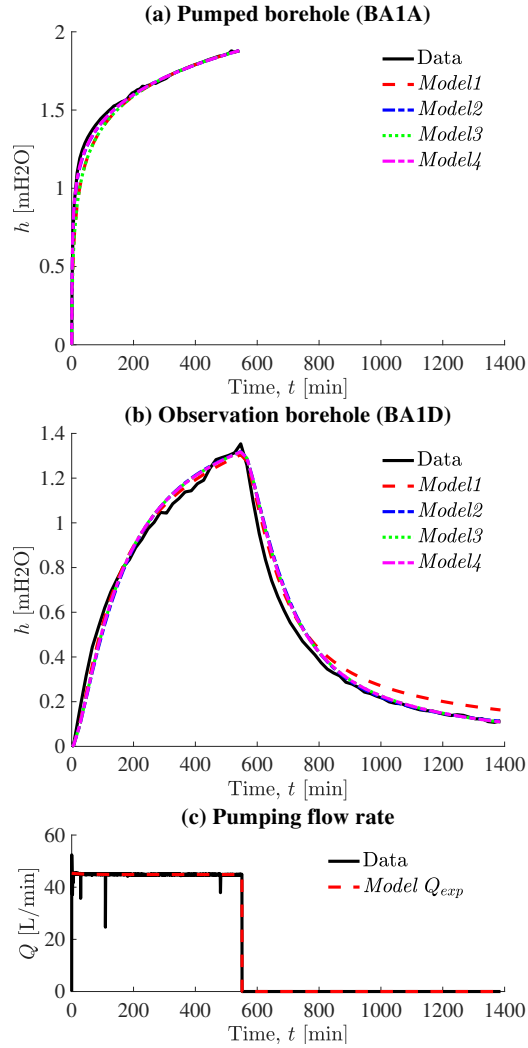


Figure 4: Data and models related to experiment *Exp1A*. The results obtained with the following models overlap: (a) *Model1-Model3* and *Model2-Model4*, (b) *Model2-Model3-Model4*.

		<i>Model1</i>	<i>Model2</i>	<i>Model3</i>	<i>Model4</i>
Pump. well	<i>N</i>	2	1.67	2	1.64
	<i>K</i>	2.05×10^{-4}	1.47×10^{-3}	2.04×10^{-4}	1.71×10^{-3}
	<i>B</i>	-	-	373.69	213.34
Obs. well	<i>N</i>	2	2.27	2	2.27
	<i>K</i>	1.97×10^{-4}	3.48×10^{-5}	1.89×10^{-4}	3.53×10^{-5}
	<i>S_s</i>	7.59×10^{-4}	1.35×10^{-4}	6.55×10^{-4}	1.37×10^{-4}
	<i>B</i>	-	-	193.76	1695.73
	σ_w	42.56	10.11	52.10	10.28

Table 3: Properties estimated for the models and data presented in Figure 4 (*Exp1A*).

334 *3.1.2. Pumping test in borehole BA1D*

335 In experiment *Exp1D*, the pumping was applied in borehole BA1D for
336 355 minutes and the flow rate decreased from 26.7 to 24.1 L/min (Figure 5c).
337 The collected data and the corresponding acceptable models are shown in
338 Figure 5 and Table 4. As for *Exp1A*, a common model reproducing the
339 data collected in both the pumped and observation boreholes could not be
340 found. Concerning the data collected in the pumped borehole (Figure 5a),
341 *Model1* and *Model3* provide an acceptable fit and the transmissivity value
342 estimated with *Model1* is consistent with that of Theis' method, which is
343 equal to 2.15×10^{-5} m²/s. The best fit is obtained with *Model3*, whereas
344 *Model2* does not provide an acceptable fit and *Model4* does not improve the
345 results obtained with *Model3*. These results show the importance of leakage
346 processes for reproducing the data observed in borehole BA1D, as well as
347 the presence of open fractures that intersect the well ($N = 2$ and $\sigma_w < 0$ for

348 $S_s < 3 \times 10^{-2} \text{ m}^{-1}$ from additional simulations).

349 Regarding the data collected in the observation borehole, we obtain a
 350 correct fit with all the models, whereas interpreting the end of the recovery
 351 with Theis's method is not possible because the recovery is not developed
 352 enough. *Model3* is considered as the best-fitting model because the large
 353 values of skin factor in *Model1* and *Model2* are not realistic and *Model4* does
 354 not improve the results.

		<i>Model1</i>	<i>Model2</i>	<i>Model3</i>	<i>Model4</i>
Pump. well	<i>N</i>	2	1.83	2	2
	<i>K</i>	2.02×10^{-5}	1.61×10^{-4}	4.5×10^{-6}	4.47×10^{-6}
	<i>B</i>	-	-	31.04	31.04
Obs. well	<i>N</i>	2	1.8	2	1.45
	<i>K</i>	3.21×10^{-4}	1.19×10^{-3}	3.96×10^{-6}	2×10^{-5}
	<i>S_s</i>	3.08×10^{-4}	1.12×10^{-3}	2.9×10^{-5}	1.43×10^{-4}
	<i>B</i>	-	-	5	4
	σ_w	206.91	594.53	1.39	54

Table 4: Properties estimated for the models and data presented in Figure 5 (*Exp1D*).

355 3.2. Multi-level pumping tests

356 3.2.1. Pumping tests in borehole BA1A

357 The multi-level pumping experiments conducted in borehole BA1A lead
 358 to the data and models shown in Figure 6 and Table 5 for experiment
 359 *Exp2A_i1A* and Figure 7 and Table 6 for experiment *Exp2A_i2A*. No re-
 360 sults are presented for experiment *Exp2A_i3A* because it was not possible
 361 to pump in the considered interval (133-400 m). In this case, we estimate

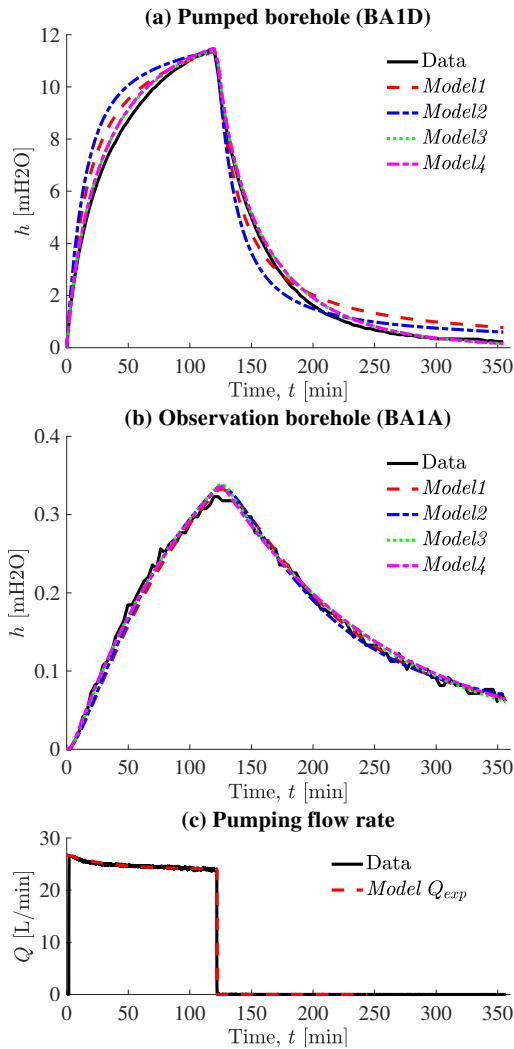


Figure 5: Data and models related to experiment *Exp1D*. The results obtained with *Model3* and *Model4* overlap.

362 that the transmissivity of this zone is smaller than 7×10^{-8} m²/s, which
 363 is the smallest transmissivity in which we could pump with that pumping
 364 equipment.

365 In experiment *Exp2A_i1A*, a multiple-step pumping flow rate is applied

366 (Figure 6c). The data collected in the pumped (Figure 6a) and observation
367 (Figure 6b) wells are interpreted by dividing the pumping flow rate data into 5
368 sub-steps in order to account as thinly as possible for the flow rate variations,
369 and are modeled by considering flow-rate-dependent values of the skin factor
370 σ_w (Figure 6d). Note that the flow-rate dependence of the skin factor has
371 been observed and studied in previous work, in particular in step-drawdown
372 tests (Jacob, 1947; Rorabaugh, 1953; van Everdingen, 1953; Kruseman and
373 de Ridder, 1990). Furthermore, the model parameters provided in Table 5
374 are characteristic of flow in fractured media with $\sigma_w < 0$ when $N = 2$ for
375 *Model1* and *Model3* and $N = 1$ for *Model2* and *Model4*.

376 The flow dimension of *Model2* and *Model4* indicates the presence of a
377 channel, or several independent channels, that dominate the flow. The high
378 values of σ_w estimated with these models show either (i) clogging of the
379 channel that intersects the pumping well or (ii) the channel does not intersect
380 the pumping well and hydraulic connection occurs through permeable porous
381 media or fissures. Note that the high values of σ_w can be explained by the
382 fact that the interpretation of the skin factor with the generalized radial flow
383 model is not explicit when $N \neq 2$ because the pumping chamber geometry of
384 the model does not correspond to its real geometry. The difference between
385 these two geometries impacts the value of the skin factor, which could explain
386 why high values of the skin factor can be found for low flow dimension (Hamm
387 and Bidaux, 1996; Lods and Gouze, 2004). *Model2* is selected as the most
388 realistic model because (i) it provides a much better fit with the collected
389 data than *Model1* with an almost-linear increase of the skin factor and (ii)
390 *Model3* and *Model4* do not improve the results obtained with *Model2*. The

391 transmissivity values estimated with Theis' method are 5 times greater than
 392 those obtained for the pumped and observation boreholes with *Model1*, which
 393 is explained by the inadequacy of *Model1*.

	<i>Model1</i>	<i>Model2</i>	<i>Model3</i>	<i>Model4</i>
N	2	1	2	1
K	2.37×10^{-5}	1.6×10^{-2}	2.31×10^{-5}	1.56×10^{-2}
S_s	1.12×10^{-3}	1.1×10^{-1}	1.1×10^{-3}	1.09×10^{-1}
B	-	-	55.57	172.79
σ_w	cf Figure 6d			

Table 5: Properties estimated for the models and data presented in Figure 6 (*Exp2A.i1A*).

394 For experiment *Exp2A.i2A*, a common model reproducing the data col-
 395 lected in the pumped and observation boreholes could not be found. The
 396 results presented in Figure 7 and Table 6 show that the fit to the data that
 397 is obtained with *Model1* can be improved with *Model3*, whereas *Model2* and
 398 *Model4* do not improve these results. The transmissivity values estimated
 399 with Theis's method are equal to 1.06×10^{-5} m²/s and 3.94×10^{-5} m²/s for
 400 the pumped and observation boreholes, respectively, corresponding to larger
 401 and smaller values, respectively, than that obtained with *Model1*.

402 3.2.2. Pumping tests in borehole BA1D

403 The data and models related to the multi-level pumping tests conducted
 404 in borehole BA1D are shown in Figure 8 and Table 7 for experiment *Exp2D.i1D*,
 405 Figure 9 and Table 8 for experiment *Exp2D.i2D*, and Figure 10 and Table 9
 406 for experiment *Exp2D.i3D*. For experiments *Exp2D.i1D* and *Exp2D.i2D*, a
 407 common model could not be found to reproduce the data collected in both

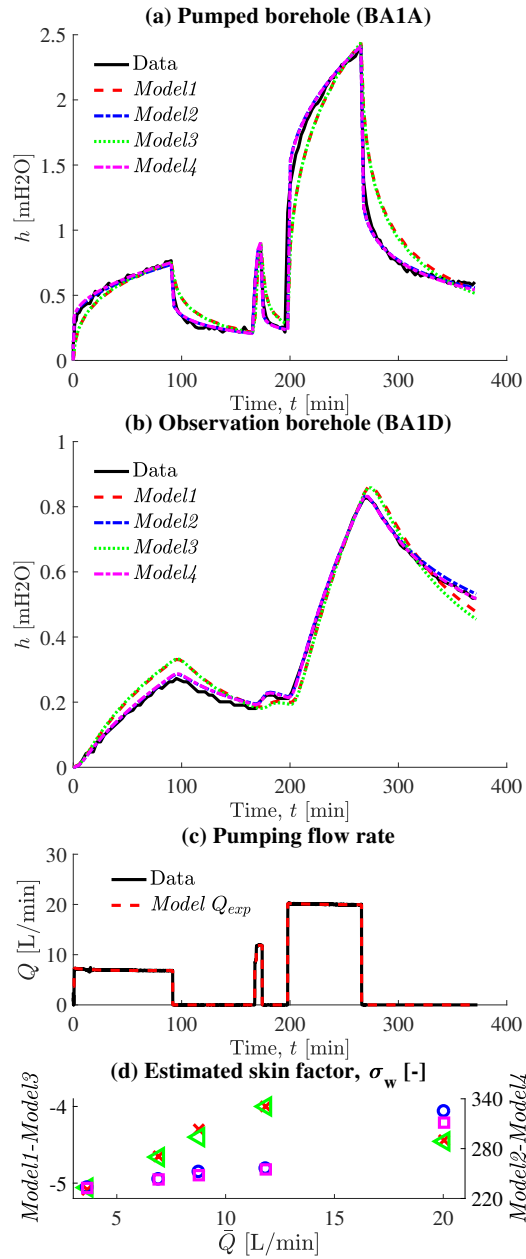


Figure 6: Data, models, and parameters related to experiment *Exp2A-i1A*. (a-b) The results obtained with the following models overlap: *Model1-Model3* and *Model2-Model4*. In (d) the changes in the estimated skin factor σ_w with the step average flow rate \bar{Q} are shown for *Model1-Model3* (red crosses-green triangles, left axis) and *Model2-Model4* (blue circles-magenta squares, right axis).

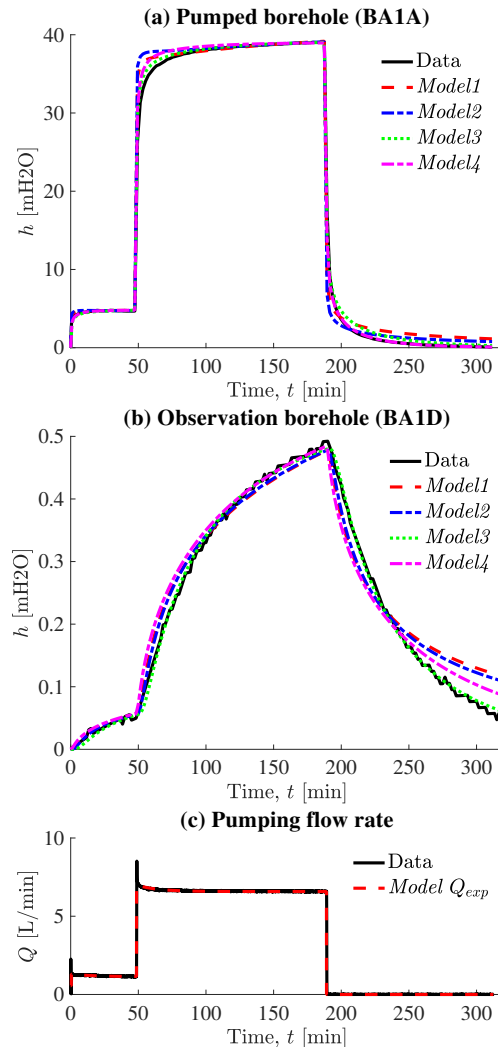


Figure 7: Data and models related to experiment *Exp2A_i2A*.

408 the pumped and observation boreholes, implying that the models are defined
 409 for each borehole. For experiment *Exp2D_i3D*, no response was observed in
 410 the observation borehole implying that the models are only defined for the
 411 pumped borehole.

412 Concerning experiment *Exp2D_i1D*, the results reported in Figure 8a and

		<i>Model1</i>	<i>Model2</i>	<i>Model3</i>	<i>Model4</i>
Pump. well	<i>N</i>	2	2.1	2	2
	<i>K</i>	6.15×10^{-6}	4.59×10^{-6}	2.74×10^{-6}	2.65×10^{-6}
	<i>B</i>	-	-	28.53	22.41
Obs. well	<i>N</i>	2	2.2	2	1.2
	<i>K</i>	5.6×10^{-5}	1.54×10^{-5}	2.5×10^{-5}	10^{-2}
	<i>S_s</i>	2.41×10^{-4}	9.74×10^{-5}	3.24×10^{-4}	8.64×10^{-3}
	<i>B</i>	-	-	24.88	111.24
	σ_w	0	0	0	$-2.9 \times 10^{-4}; -7 \times 10^{-5}$

Table 6: Properties estimated for the models and data presented in Figure 7 (*Exp2A_i2A*).

413 Table 7 show that *Model1* and *Model2* do not provide an acceptable fit of
414 the recovery data recorded in the pumped borehole, whereas *Model3* and
415 *Model4* fit well the data. The best-fitting model (*Model4*) corresponds to a
416 non-cylindrical flow that is dominated by a channel ($N = 1$) with important
417 leakage ($B = 2.92$). Additional simulations show that $\sigma_w < 0$ when $S_s <$
418 $2 \times 10^{-1} \text{ m}^{-1}$, which indicates the presence of open fractures that intersect the
419 well. Similar results are observed for the data collected in the observation
420 borehole since the fit obtained with *Model1* could not be improved with
421 *Model2* whereas *Model3* and *Model4* fit well the data, the best fit being
422 obtained with *Model4* (Figure 8b). In this case, σ_w has no effect on the results
423 ($\sigma_w = 0$), implying that the estimated values of K/S_s and S_s are reliable, the
424 high values of S_s being characteristic of semi-confined aquifers. Finally, the
425 hydraulic conductivity values estimated with *Model1* are consistent with the
426 transmissivity values obtained using Theis' method, which give 5.53×10^{-6}

and $1.37 \times 10^{-4} \text{ m}^2/\text{s}$ for the pumped and observation well, respectively.

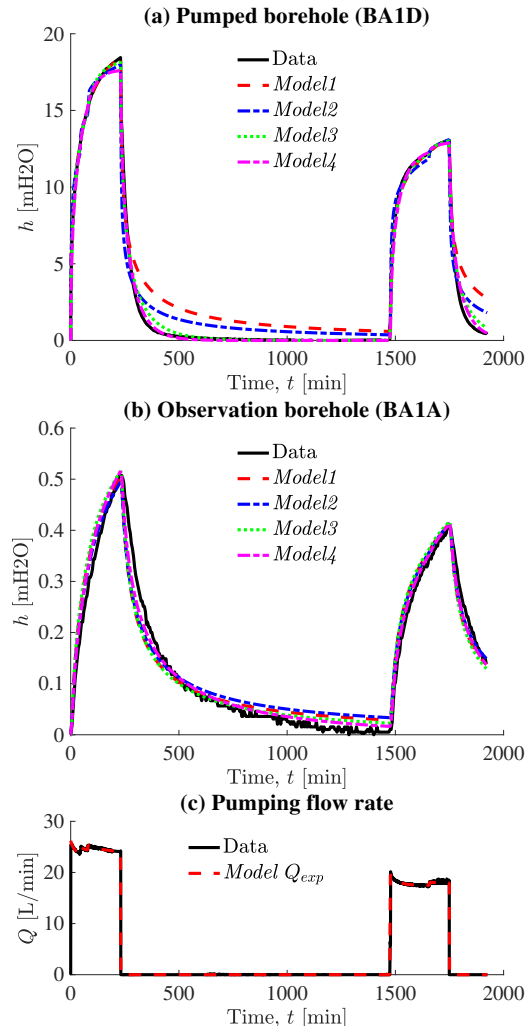


Figure 8: Data and models related to experiment *Exp2D.i1D*.

427

428 When studying the interval 102-132 m (experiment *Exp2D.i2D*), we con-
 429 sider the four-step pumping flow rate presented in Figure 9c. Figure 9a shows
 430 that *Model1* and *Model2* do not fit the recovery, whereas *Model3* and *Model4*
 431 provide a perfect fit to the data collected in the pumped borehole, resulting

		<i>Model1</i>	<i>Model2</i>	<i>Model3</i>	<i>Model4</i>
Pump. well	<i>N</i>	2	2.05	2	1
	<i>K</i>	9.4×10^{-6}	1.06×10^{-5}	3.94×10^{-6}	1.3×10^{-4}
	<i>B</i>	-	-	17.13	2.92
Obs. well	<i>N</i>	2	1.89	2	1.67
	<i>K</i>	1.92×10^{-4}	3.68×10^{-4}	1.84×10^{-4}	1.26×10^{-3}
	<i>S_s</i>	1.38×10^{-3}	2.49×10^{-3}	1.34×10^{-3}	7.83×10^{-3}
	<i>B</i>	-	-	197.35	105.4
	σ_w	0	0	0	0

Table 7: Properties estimated for the models and data presented in Figure 8 (*Exp2D-i1D*).

432 in considering the simplest model (i.e., *Model3*) as the best-fitting model.
433 For the data collected in the observation borehole, all models provide an
434 acceptable fit to the data, implying that the simplest model (i.e., *Model1*)
435 is considered as the best-fitting model. In the case of the pumped-borehole
436 models, the decrease in the slope of σ_w versus \bar{Q} when $\bar{Q} = 1.79$ L/min (Fig-
437 ure 9d) is characteristic of unclogging phenomena, while the good fit between
438 the collected and simulated data suggests that these phenomena are local-
439 ized in the borehole skin. Additional analyses point out that σ_w is negative
440 only when S_s is smaller than $1.9 \times 10^{-5} \text{ m}^{-1}$, which indicates the absence of
441 fractures that intersect the wells with apertures larger than in the formation.

442

443 Because of the low permeability of the interval 133-400 m (experiment
444 *Exp2D-i3D*), very small flow rates were applied when studying this zone
445 (Figure 10b). During this experiment, no response was recorded in the ob-

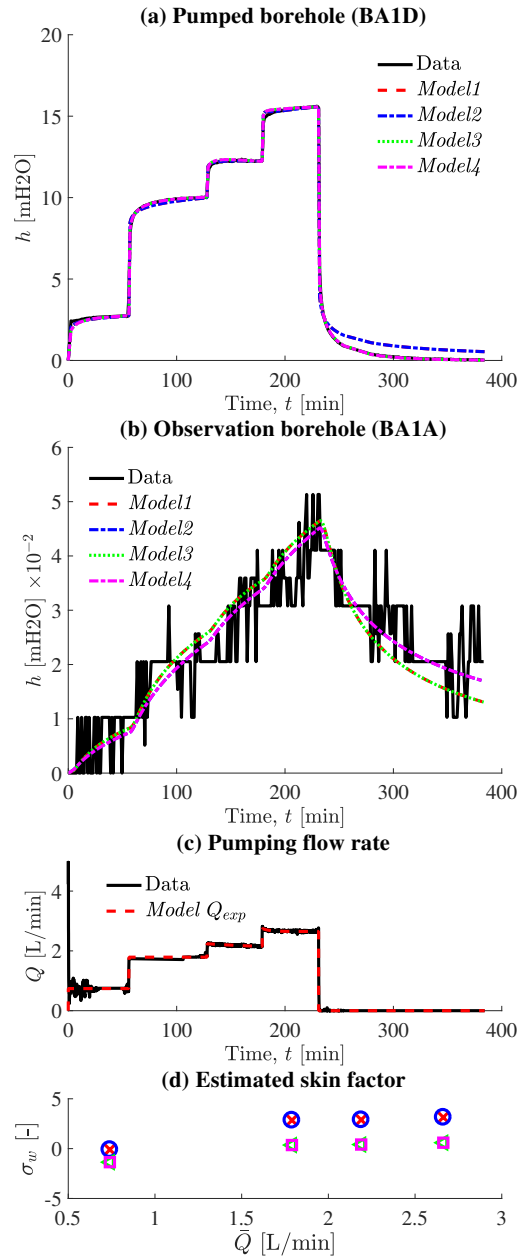


Figure 9: Data and models related to experiment *Exp2D.i2D*. The results obtained with the following models overlap: (a) *Model1-Model2* and *Model3-Model4*, (b) *Model1-Model3* and *Model2-Model4*. In (d) the changes in the estimated skin factor σ_w with the step average flow rate \bar{Q} are shown for *Model1* (red crosses), *Model2* (blue circles), *Model3* (green triangles) and *Model4* (magenta squares).

		<i>Model1</i>	<i>Model2</i>	<i>Model3</i>	<i>Model4</i>
Pump. well	<i>N</i>	2	2	2	2
	<i>K</i>	4.5×10^{-6}	4.5×10^{-6}	2.49×10^{-6}	2.49×10^{-6}
	<i>B</i>	-	-	10.03	10.03
Obs. well	<i>N</i>	2	1.51	2	1.51
	<i>K</i>	1.79×10^{-4}	3.79×10^{-3}	1.79×10^{-4}	3.79×10^{-3}
	<i>S_s</i>	1.54×10^{-3}	1.89×10^{-2}	1.54×10^{-3}	1.89×10^{-2}
	<i>B</i>	-	-	-	-
	σ_w	0	0	0	0

Table 8: Properties estimated for the models and data presented in Figure 9 (*Exp2D_i2D*).

446 servation borehole BA1A and the small flow rates were difficult to apply and
 447 maintain, resulting in irregular initial flow rates. In this case, the response
 448 recorded in the pumped borehole is interpreted by dividing the pumping flow
 449 rate data into 9 sub-steps. The results shown in Figure 10a and Table 9 are
 450 obtained by using, as before, a step-wise exponential model to reproduce the
 451 pumping flow rate in *Model1*, *Model2*, *Model3* and *Model4* (dashed red curve
 452 in Figure 10b). In order to demonstrate the importance of this exponential
 453 model, we also show the results obtained with *Model3'*, which considers a
 454 step-wise constant pumping flow rate (dash-dot blue curve in Figure 10b).
 455 These results show that *Model1* does not provide an acceptable fit to the data
 456 because, namely, of an important increase in the drawdown at the beginning
 457 of the last pumped steps. Attempt to reduce these peaks leads to models
 458 with unrealistic values of the wellbore storage coefficient (not shown). On
 459 the contrary, these peaks are eliminated with *Model2*, *Model3* and *Model4*,

460 *Model3* being the best-fitting model. The transmissivity value estimated
 461 with *Model1* is consistent with that of the standard Theis' method, which
 462 is equal to 6.71×10^{-8} m²/s. Furthermore, Figure 10c shows that increas-
 463 ing \bar{Q} from 0.079 to 0.267 L/min with *Model1*, *Model2*, *Model3* and *Model4*
 464 results in decreasing σ_w . This behavior is characteristic of the occurrence
 465 of an unclogging phenomenon. On the contrary, when using *Model3'*, this
 466 skin factor behavior is not observed (not shown) and a large discrepancy
 467 is observed during the recovery between the simulated and collected data
 468 (dotted black curve in Figure 10a), demonstrating the importance of using a
 step-wise exponential model for representing the pumping flow rate.

	<i>Model1</i>	<i>Model2</i>	<i>Model3</i>	<i>Model4</i>
<i>N</i>	2	2.99	2	2.09
<i>K</i>	6.99×10^{-8}	1.32×10^{-8}	2.3×10^{-8}	2.11×10^{-8}
<i>B</i>	-	-	0.21	0.26

Table 9: Properties estimated for the models and data presented in Figure 10 (*Exp2D-i3D*).

469

470 3.3. Cross-borehole multi-level-monitoring pumping experiment

471 In experiment *Exp3D*, a pumping flow rate of 20.17 L/min was applied
 472 during 338 min in borehole BA1D while monitoring the pressure in the in-
 473 tervals *i1A'* (22-107 m), *i2A* (108-132 m), and *i3A* (133-400 m) in borehole
 474 BA1A (Figure 11). Here, the data cannot be interpreted with the models
 475 presented before because the flow rate applied to each interval is not known.
 476 The data collected during this experiment are rather used to confirm and
 477 complete the information previously obtained on the connections between

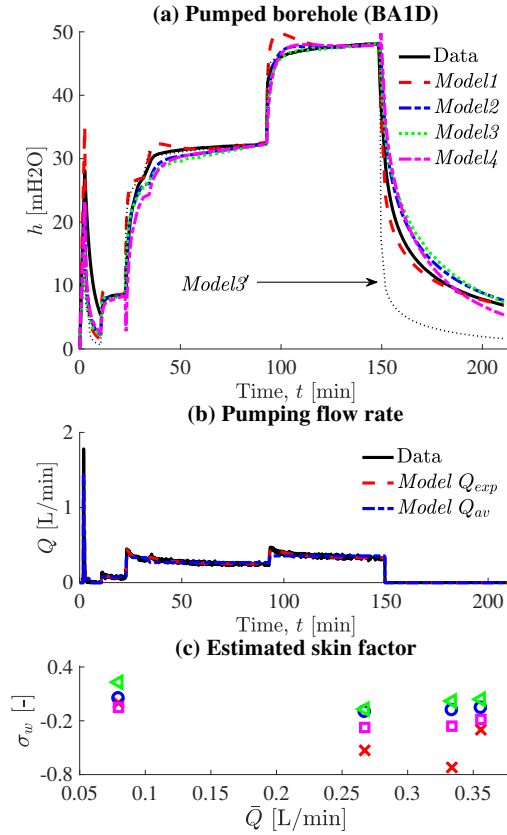


Figure 10: Data, models, and parameters for experiment *Exp2D-i3D*. In (c) the changes in σ_w with the step average flow rate \bar{Q} are shown for *Model1* (red crosses), *Model2* (blue circles), *Model3* (green triangles) and *Model4* (magenta squares).

478 the pumped and observation boreholes, as well as between various intervals
 479 of these boreholes.

480 From the data reported in Figure 11, we determine that the reaction
 481 times of intervals $i1A'$, $i2A$, and $i3A$ are 4, 1, and 9 min, respectively. These
 482 observations can be related to the results presented in Section 3.2.1 where the
 483 multi-level pumping tests conducted in borehole BA1A are interpreted with
 484 various models. Using *Model1* leads to show that (i) the diffusivity estimated

485 in interval $i1A$ is smaller than that of interval $i2A$ since $K/S_s = 2.12 \times$
 486 10^{-2} m²/s in $Exp2A_i1A$, and 2.16×10^{-1} (pumping borehole) and $2.32 \times$
 487 10^{-1} m²/s (observation borehole) in $Exp2A_i2A$, and (ii) the transmissivity
 488 of $i3A$ is below the capability of our pumping equipment since it was not
 489 possible to pump in $Exp2A_i3A$. Considering that interval $i1A$ is included
 490 into $i1A'$, the reaction times defined from experiment $Exp3D$ are consistent
 491 with the results from experiments $Exp2A$.

492 The reaction of interval $i3A$ reported in Figure 11 also indicates that
 493 there is a connection between this interval and borehole BA1D whereas the
 494 results of $Exp2D_i3D$ show that this interval is not hydraulically connected
 495 to interval $i3D$ of borehole BA1D. This demonstrates that interval $i3A$ is
 496 connected to borehole BA1D through non-horizontal flow. This is consistent
 497 with the leakage models of experiments $Exp2D_i2D$ and $Exp2D_i3D$, which
 result in the presence of vertical flow between intervals $i2D$ and $i3D$.

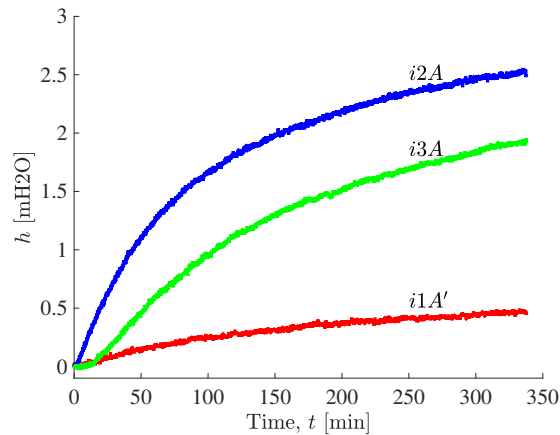


Figure 11: Data monitored in intervals $i1A'$, $i2A$ and $i3A$ of the observation borehole BA1A while pumping in borehole BA1D (experiment $Exp3D$).

498

499 4. Discussion

500 The parameters inferred from modelling the pumped well drawdown re-
501 veal the hydraulic properties in the vicinity of the pumping well. Conversely,
502 those evaluated from the observation well data are effective parameters in-
503 tegrating all the hydraulic structures from surface to depth including local
504 draining zones. Nevertheless, the parameters evaluated at the observation
505 well, when different from those inferred at the pumping well, enlighten the
506 heterogeneity and probable anisotropy of the studied system.

507 Figure 12 summarizes the main conclusions that are obtained from the
508 (non-unique) models presented in Section 3, including the open-borehole tests
509 *Exp1A* and *Exp1D* and the cross-borehole multi-level hydraulic experiments
510 *Exp2A* and *Exp2D*. Interpreting the open-borehole tests *Exp1A* and *Exp1D*
511 with *Model1* leads to a transmissivity of BA1D one order of magnitude lower
512 than that of BA1A with leakage in the former case. These results, which are a
513 first indication of the horizontal and vertical heterogeneities that characterize
514 the system, are consistent with the open-borehole experiments in Dewandel
515 et al. (2005) that could be interpreted with $N = 2$. Furthermore, in the
516 case of *Exp1D*, the need for considering important leakage processes can be
517 related to the presence of an overlying aquifer zone located above BA1D
518 casing base depth, in the alluvium (Figure A.16), at which a productive
519 interval (26-27 m) is detected by the flowmeter (Figure A.14c).

520 Concerning the cross-borehole multi-level hydraulic experiments *Exp2A*
521 and *Exp2D*, the presented results emphasize the strong variability of the hy-
522 draulic properties induced by the heterogeneities of the geological structures.
523 For the upper part of the system (i.e., intervals *i1A* and *i1D* located between

524 41 and 75 m), results indicate the presence of highly conductive fractures
525 ($N < 2$ in *Exp2A_i1A* and *Exp2D_i1D*) with different behaviors depend-
526 ing on the considered pumped borehole. When pumping in borehole BA1A
527 (*Exp2A_i1A*), a unique model with $N = 1$ is found to interpret the data col-
528 lected in both boreholes. This shows that the hydraulic responses of BA1A
529 and BA1D are driven by a highly conductive channelized structure ($N = 1$),
530 for example an extended, open or partially mineralized fracture within which
531 a 1D channel is developed. The two boreholes do not necessarily intersect
532 the channel, they can be connected to it by a conduct in which the flow
533 rate becomes rapidly permanent. On the contrary, when pumping in BA1D
534 (*Exp2A_i1D*), two different leakage models are required to describe the data
535 collected in the boreholes with an increase in the hydraulic conductivity and
536 flow dimension from the pumped to the observation-borehole model. In this
537 case, the need for leakage models with high values of the leakages for the
538 pumped-borehole model, as well as the heterogeneities in properties between
539 the boreholes with $N > 1$ for the observation-borehole model, show that the
540 hydraulic responses are only partially determined by the highly conductive
541 channelized structure previously described. That is, the water pumped in
542 the upper tested interval of BA1D comes from the highly conductive chan-
543 nelized structure previously described that connect the upper intervals of the
544 considered boreholes (horizontal connections), but also from underlying and
545 overlying rocks surrounding BA1D (vertical connections). Thus additional
546 vertical flow contributions are present when pumping in BA1D, whereas the
547 horizontal connections are sufficient for the pumping in BA1A with similar
548 pumping flow rates.

549 Concerning the middle part of the system (i.e., intervals *i2A* and *i2D*
550 located between 102 and 132 m), the value of the estimated flow dimen-
551 sion ($N = 2$) for the pumped and observation boreholes in *Exp2A_i2A* and
552 *Exp2D_i2D*, shows that the observed hydraulic responses are not determined
553 by the presence of conductive structures with channelized flow as for the
554 upper part of the system. Conversely, these models are related to leakage
555 properties except for the observation-borehole model of *Exp2D_i2D* for which
556 a high value of the hydraulic conductivity is obtained ($K = 1.8 \times 10^{-4}$ m/s).
557 This indicates the presence of heterogeneities in the directions of the flows
558 that contribute to the pumping: (i) the pumping in BA1A is supplied by
559 both horizontal and vertical flows that are located around and far from the
560 pumped borehole, and (ii) the pumping in BA1D is supplied by horizontal
561 and vertical flows close to the pumped borehole, and only horizontal flows
562 around borehole BA1A. This might be related to the location of BA1A for
563 which highly conductive structures of the upper part of the system was de-
564 tected (see above). Indeed, considering that BA1A is surrounded by these
565 structures, one can speculate that they contribute to the water pumped in
566 BA1D by flowing from the upper to the middle part of the system through
567 borehole BA1A and flowing horizontally in the middle part of the system
568 from BA1A to BA1D. This explains that there is no vertical flow around
569 BA1A when pumping in BA1D and that there is no counterpart behavior
570 observed when pumping in BA1A.

571 Finally, the pumping experiments conducted by isolating the lower part
572 of the system (i.e., intervals *i3A* and *i3D* located between 133 and 400 m)
573 also show a potential impact of the localization of the wells regarding the

574 conductive structures of the system. Whereas it was not possible to pump
575 water from BA1A (*Exp2A.i3A*) because the transmissivity of this layer was
576 too low, we observe a different behavior in BA1D for which the data col-
577 lected in the pumped borehole are well described with a leakage model
578 (*Exp2D.i3D*). In this case, the pumped water is supplied by vertical con-
579 nections occurring around the pumped borehole, which are coming from the
580 middle part of the system that is located directly above the considered area
581 (i.e., without intermediary poorly-permeable zones) and connected to the
582 upper highly transmissive part of the system through BA1A. The differences
583 between *Exp2A.i3A* and *Exp2D.i3D* can be explained by heterogeneities in
584 the vertical hydraulic properties implying that there is no flow exchanges be-
585 tween the middle and lower parts of the system in the former case, whereas
586 these exchanges occur in the latter.

587 **5. Conclusions**

588 The cross-borehole multi-level hydraulic experiments presented in Sec-
589 tion 3 show a complex behavior of the ophiolitic hard-rock aquifer located
590 within the BA1 site of the Sultanate of Oman. The discussion provided
591 in Section 4 explains this behavior by the presence of highly transmissive
592 structures in the upper part of the system and different locations of the
593 boreholes into these structures, resulting in strong geological and hydraulic
594 heterogeneities in all directions. Within a 15 m area, this study reveals de-
595 grees of heterogeneities going from 1D channelized flows sparsely connected
596 to far-field resources to 2D standard systems supplied by nearby surrounding
597 ZONES.

598 The characterization previously described required to conduct hydraulic
599 tests in zones with variable permeability going from highly to poorly con-
600 ductive areas. In the latter case, pumping at very small flow rates (smaller
601 than 1 L/min) is a technical challenge for which decreasing flow rates cannot
602 be avoided. Whereas this behavior has never been considered in the data
603 interpretation of existing studies, we developed models that are able to take
604 into account this feature, and we show that this characteristic of the pumping
605 flow rate is critical for interpreting the experiments.

606 The experiment interpretation was done using four transient radial so-
607 lutions relying on various assumptions going from cylindrical flow without
608 leakage to generalized radial flow with leakage. We believe that the data
609 analysis methodology and the parameter estimation strategy developed for
610 this work should be useful for interpreting other pumping experiments specif-
611 ically in low permeability heterogeneous systems and when vertical leakages
612 are important. In addition, the efficiency of these semi-analytical models
613 makes them an ideal tool for conducting parametric sensitivity analysis and
614 inverting experimental data in the context of complex parameter sets.

615 The use of fractional flow models is justified in this work by direct geolog-
616 ical observations and the need to consider vertical leakages, and confirmed by
617 the satisfying curve-fitting and coherent parameter and property estimates.
618 Despite the fractured nature of ophiolitic aquifers, the adequacy of the dual-
619 permeability concept for describing these systems is an open question, in
620 particular because there is no evidence of large-scale fractures embedded
621 into a poorly-permeable matrix as observed for granitic systems. The doubt
622 about a potential dual-permeability behavior of ophiolitic aquifers requires to

623 integrate vertical leakages in such models and to collect additional data such
624 as breakthrough curves from chemical tracer experiments. Future work for
625 the site considered in this study will focus on this characterization method
626 with the objective of improving our ability to characterize ophiolitic aquifers
627 and understanding their behavior.

628 **Notations**

S_s	Aquifer specific storage [m^{-1}]
K	Hydraulic conductivity [m s^{-1}]
$T = bK$	Transmissivity [$\text{m}^2 \text{s}^{-1}$]
B	Leakage factor [m]
β	Leakage parameter [m^{-2}]
h	Drawdown [m]
r	Distance from the well [m]
629 N	Flow dimension [-]
r_w	Well-aquifer exchange radius [m]
b	Ortho-radial extent [m]
S_w	Well storage coefficient [m^2]
σ_w	Skin factor [-]
Q	Pumping flow rate [$\text{m}^3 \text{s}^{-1}$]
\bar{Q}	Pumping step average flow rate [$\text{m}^3 \text{s}^{-1}$]

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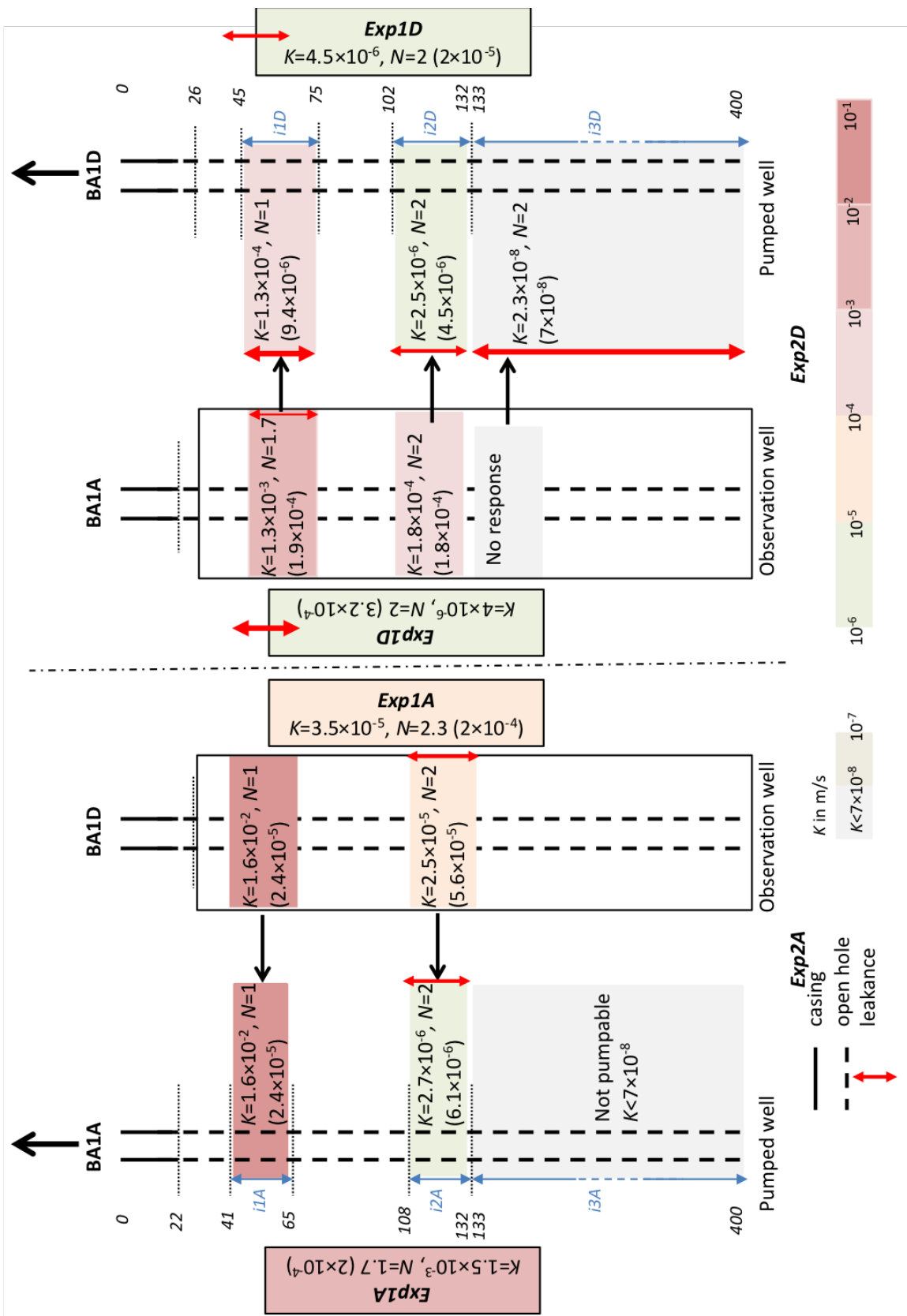


Figure 12: Summary of the models and properties estimated from the pumping experiments *Exp1A*, *Exp1D*, *Exp2A* and *Exp2D*. The numbers written in italic denote the distance from the surface. K and N are the hydraulic conductivity (in m/s) and flow dimension, respectively, estimated with the best-fitting model of each experiment. For each experiment, the value of K estimated with *Model1* is also provided (value in brackets) in order to compare the integrated conductive properties. The thickness of the red arrow characterizes the importance of the leakage process.

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645 **Appendix A. Additional data**

646 Vertical heterogeneities of boreholes BA1A and BA1D were investigated
647 by measuring the temperature profiles in the boreholes (Figure A.13) and
648 conducting flowmeter tests under ambient and forced hydraulic conditions
649 (Figure A.14). The temperature profiles are obtained with the multi pa-
650 rameter probe ALT QL40 OCEAN, which allows measuring temperature
651 between 0 and 50 °C, and the flowmeter data are obtained with the heat
652 pulse flowmeter Mount Sopris HFP-2293, which allows measuring flow rates
653 between 0.1 to 4 L/min. The data obtained under forced hydraulic condi-
654 tions were collected while pumping at a flow rate of 18.12 and 4.47 L/min in
655 boreholes BA1A and BA1D, respectively. The full temperature profiles show
656 temperature anomalies for both boreholes above 61 m (Figure A.13a), and
657 their enlargement between 115 and 155 m shows a temperature anomaly at
658 depth 130-131 m in borehole BA1A (Figure A.13b). From the flowmeter data
659 collected in borehole BA1A, we observe changes in the vertical flow rates at
660 depth 22-29 m in Figure A.14a and at depth 33-39, 45-46 and 58-59 m in
661 Figure A.14b. Finally, the flowmeter data collected in borehole BA1D and
662 displayed in Figure A.14c show changes in the vertical flow rates at depth
663 26-27, 62-64 and 105-130 m. These conductive zones are reported in Ta-
664 ble A.10 with the corresponding intervals that are considered for the packer
665 experiments in order to characterize these zones. The isolated intervals are
666 chosen such that they include the conductive zones and they are located at
667 comparable positions for both boreholes.

668 While conducting the packer experiments, the pressure changes above
669 and below the isolated intervals are monitored. These pressures, denoted

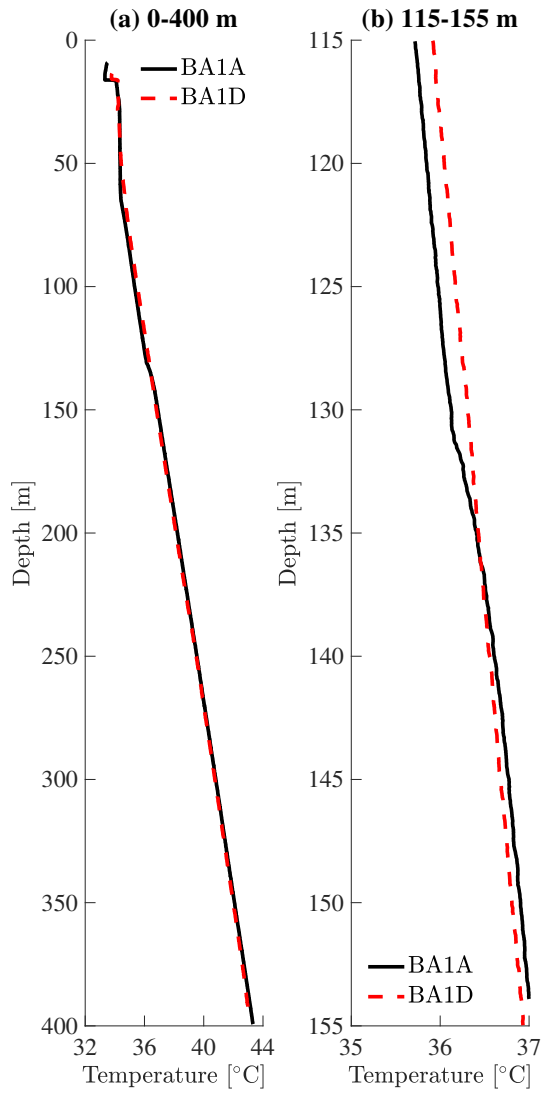


Figure A.13: Temperature profile in boreholes BA1A and BA1D (a) from 0 to 400 m and (b) from 115 to 155 m depth, showing an anomaly in temperature at depth 130-131 m in borehole BA1A.

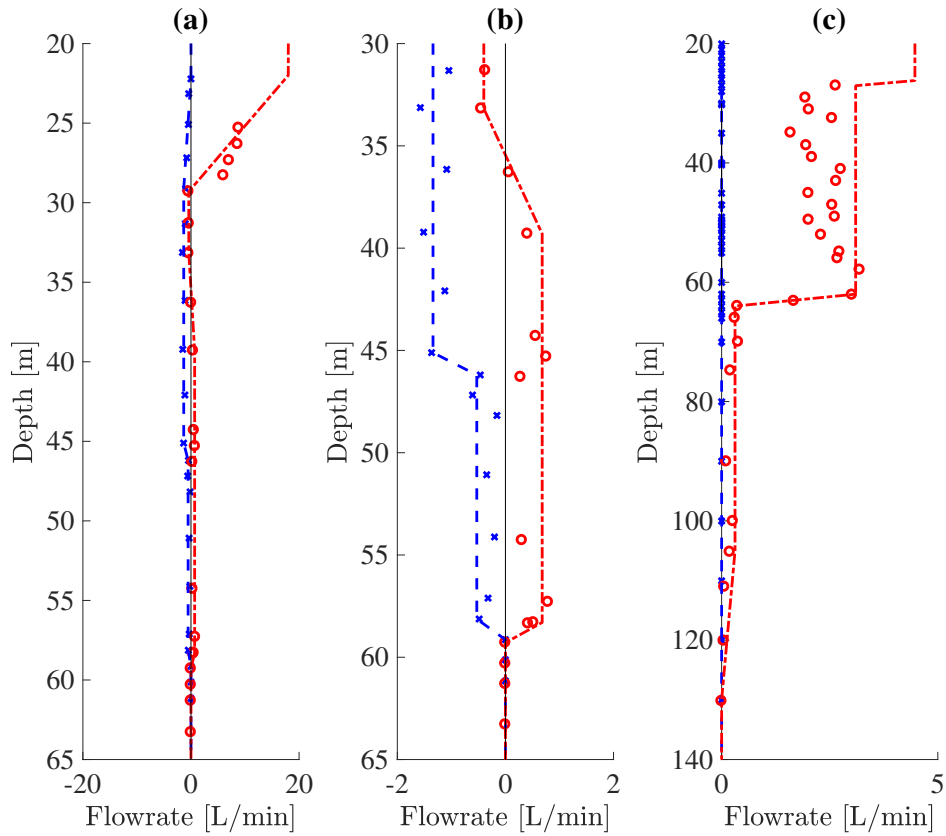


Figure A.14: Flowmeter data collected under ambient (blue crosses and dashed lines) and forced (red circles and dotted lines) hydraulic conditions in boreholes (a-b) BA1A and (c) BA1D. Symbols and (dashed and dotted) lines correspond to raw and interpreted data, respectively. The black line represent zero values of flowrate. (b) corresponds to a zoom-in of (a) for interpretation purpose. The values monitored below 65 m in (a-b) and below 140 m in (c) are null (and not shown).

670 P_1 (below) and P_3 (above), are reported in Figure A.15 for experiments
 671 *Exp2A_i1A*, *Exp2A_i2A*, *Exp2D_i1D* and *Exp2D_i2D*. The pressures are not
 672 shown for experiments *Exp2A_i3A* since the pumping could not be applied,
 673 and *Exp2D_i3D* because P_1 is not recorded for the interval located at the

Borehole	BA1A		BA1D	
Packer tests	<i>Exp2A_i1A</i>	<i>Exp2A_i2A</i>	<i>Exp2D_i1D</i>	<i>Exp2D_i2D</i>
Conductive zones	45-46; 58-59	130-131	62-64	105-130
Isolated intervals	41-65	108-132	45-75	102-132

Table A.10: Conductive zones identified from the temperature profiles and flowmeter data presented in Figures A.13 and A.14 with the corresponding packer experiments and isolated intervals that are used to characterize the zones.

674 bottom of the borehole and P_3 displays changes smaller than 0.06 mH₂O in
675 this case.

676 As additional information, we also wish to provide the lithostratigraphy in
677 boreholes BA1A and BA1D that is shown in Figure A.16. These lithological
678 logs were obtained during drilling by describing drill cuttings for every meter
679 drilled. The main bedrock lithologies are dunite and harzburgite, whereas
680 gabbro is a minor rock type that forms centimeter to decimeter thick dikes.
681 The alluvium on top of the bedrock is relatively thin with a thickness between
682 18 and 25 m, followed by a relatively thick zone of dunites to a depth of
683 160 (BA1A) and 250 m (BA1D) below surface, respectively. Harzburgite is
684 present in the deeper part of both holes. Both, the dunite and harzburgite are
685 highly altered with serpentine (lizardite and chrysotile) and brucite being the
686 dominant alteration minerals (Kelemen et al., 2020). All conductive zones,
687 detected by flowmeter logging, are within the upper dunite section of the
688 boreholes.

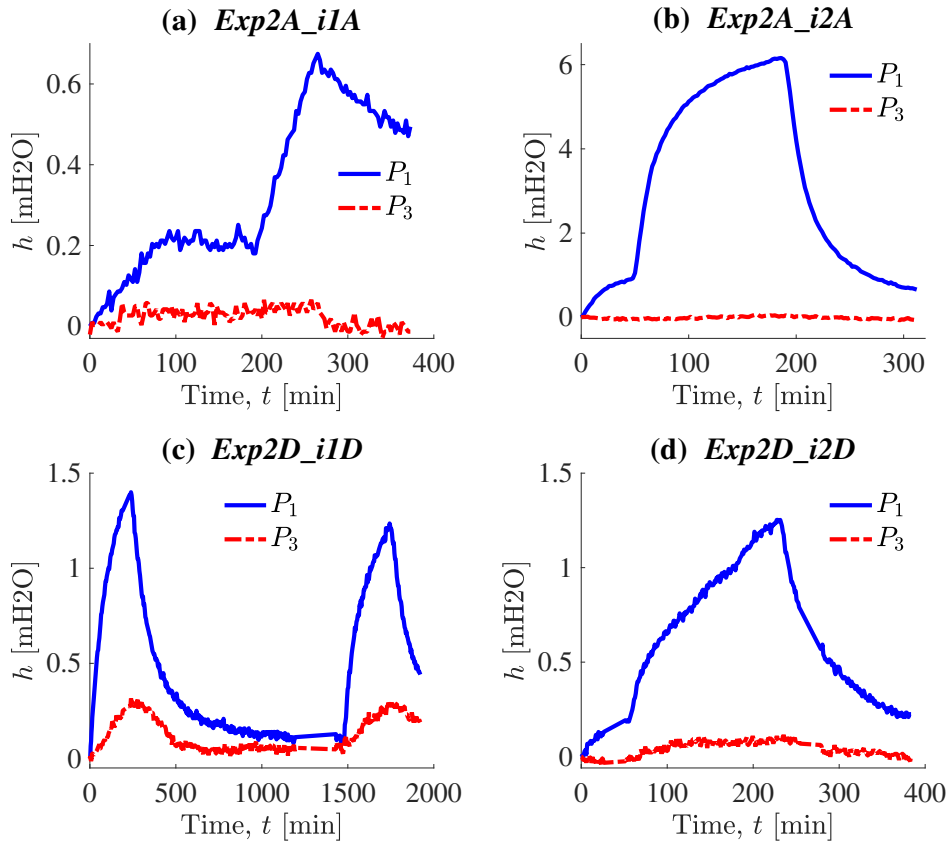


Figure A.15: Pressures P_1 (blue solid lines) and P_3 (red dotted lines) monitored below and above, respectively, the isolated interval during the packer experiments (a) *Exp2A_i1A*, (b) *Exp2A_i2A*, (c) *Exp2D_i1D* and (d) *Exp2D_i2D*.

689 Appendix B. General model

690 We wish here to formulate a model with non-integral flow dimension,
 691 vertical leakage, and transient pumping flow rates. To this end, we started
 692 from the analytical solution for transient radial flow in a fractal fractured
 693 aquifer with leakance presented in Hamm and Bidaux (1994), which combines
 694 the generalized radial flow model (Barker, 1988) with leakance (Hantush,

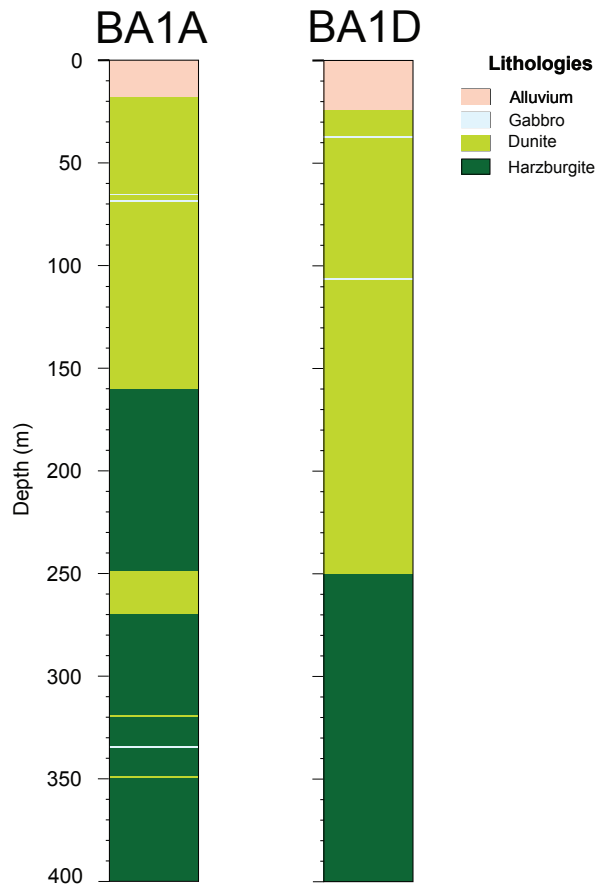


Figure A.16: Lithostratigraphic log of OmanDP holes BA1A and BA1D, showing the vertical distribution of the major lithologies.

695 1956), and extend it to time-dependent pumping flow rates and non-linear
 696 skin effects.

697 Let us consider the equations governing the drawdowns $h(r, t)$ [m] in the
 698 aquifer and $h_w(t)$ [m] in the pumping well

$$699 \quad S_s \frac{\partial h}{\partial t} = \frac{K}{r^{N-1}} \frac{\partial}{\partial r} \left(r^{N-1} \frac{\partial h}{\partial r} \right) - \frac{K}{B^2} h, \quad (B.1a)$$

$$702 \quad h(t \leq 0) = 0, \quad \lim_{r \rightarrow \infty} h = 0, \quad (B.1b)$$

704 and

$$705 \quad S_w \frac{\partial h_w}{\partial t} = G_N(b) r_w^{N-1} K \left[\frac{\partial h}{\partial r} \right]_{r=r_w} + Q, \quad (B.2a)$$

$$708 \quad h_w(t \leq 0) = 0, \quad h_w = \left[h - r_w \sigma_w \frac{\partial h}{\partial r} \right]_{r=r_w} \quad (B.2b)$$

710 with

$$711 \quad G_N(b) = \frac{2\pi^{N/2} b^{3-N}}{\Gamma(N/2)}, \quad (B.2c)$$

713 t [s] the time elapsed since the pumping starts, r [m] the distance from the
 714 pumped well, K [m s^{-1}] the hydraulic conductivity, S_s [m^{-1}] the specific stor-
 715 age, N [-] the flow dimension, B [m] the leakage factor, r_w [m] the pumping
 716 well exchange radius with the aquifer, b [m] the pumping well ortho-radial
 717 extent, S_w [m^2] the pumping well storage coefficient, σ_w [-] the pumping well
 718 skin factor, and Q [$\text{m}^3 \text{s}^{-1}$] the pumping flow rate. A full description of these
 719 parameters is provided in Barker (1988), except for the parameter B which
 720 is explained in Hantush (1956).

721 The solutions for (B.1) and (B.2) are expressed in the Laplace domain as

$$722 \quad \bar{h} = \frac{\bar{h}_w r^\nu K_\nu(\gamma r)}{A} \quad \text{and} \quad \bar{h}_w = \frac{\bar{Q}(p) A}{A S_w p + A'} \quad (B.3)$$

724 with p the Laplace variable, \bar{Q} the Laplace transform of the pumping flow
 725 rate, K_ν the modified Bessel function of the second kind and order ν ,

$$726 \quad A = r_w^\nu [K_\nu(\gamma r_w) + \sigma_w \gamma r_w K_{\nu-1}(\gamma r_w)], \quad (B.4a)$$

$$729 \quad A' = G_N(b) r_w^{N/2} K \gamma K_{\nu-1}(\gamma r_w), \quad (B.4b)$$

$$732 \quad \nu = 1 - N/2, \quad (B.4c)$$

$$735 \quad \text{and} \quad \gamma = \sqrt{\frac{pS_s}{K} + \frac{1}{B^2}}. \quad (B.4d)$$

737 Considering a pumping flow rate decreasing exponentially from Q_1 to Q_2 at
 738 time t_1 and t_2 , respectively, the equation for $Q(t)$ is

$$739 \quad Q(t) = a \exp\left(-\frac{t}{d}\right) + c, \quad (B.5a)$$

741 where the coefficients a and c are

$$742 \quad a = (Q_1 - c) \exp\left(\frac{t_1}{d}\right) \quad \text{and} \quad c = \frac{Q_2 - \delta Q_1}{1 - \delta} \quad (B.5b)$$

744 with $\delta = \exp[(t_1 - t_2)/d]$ and d being a fitting coefficient that controls the
 745 decrease shape. The Laplace transform of Q is

$$746 \quad \bar{Q}(p) = \frac{a}{p + 1/d} + \frac{c}{p}. \quad (B.6)$$

748 The solution during the recovery period (i.e., $t > t_2$) is evaluated with the
 749 superposition method by subtracting to solutions (B.3) the drawdown values
 750 $h(r, t')$ and $h_w(t')$ obtained with the flow rate $Q'(t')$, which is defined as
 751 $Q'(t') = Q(t)$ and expressed as

$$752 \quad Q'(t') = a' \exp\left(-\frac{t'}{d}\right) + c \quad (B.7)$$

754 with $a' = a \exp(-t_2/d)$ and $t' = t - t_2$.

755 Finally, the solution (B.3) obtained in the Laplace domain is inverted to
756 the time domain by using the Stehfest's algorithm (Stehfest, 1970). For step
757 drawdown tests, non-linear skin effects (i.e., the skin factor depends on the
758 flow rate (van Everdingen, 1953)) are taken into account by applying the
759 superposition method presented in Lods and Gouze (2004). For a flow rate
760 history $\{(t_i, Q_i), i = 1, n\}$, where the rate Q_i is applied between times t_i and
761 t_{i+1} , the superposed drawdown h_{sup} at time t ($t_i \leq t < t_{i+1}$) is

$$762 \quad h_{sup}(t) = \sum_{j=1}^{i-1} [h(t - t_j, Q_j) - h(t - t_{j+1}, Q_j)] + h(t - t_i, Q_i), \quad (\text{B.8})$$

763

764 where $h(t, Q)$ is the drawdown at time t produced by a flow pulse Q beginning
765 at time zero.

766 **Appendix C. Interpretation method**

767 The pumping experiments are analyzed by estimating the hydraulic pa-
768 rameters that give the best fit between the data collected and several an-
769 alytical models. These models rely on the analytical solution presented in
770 Appendix B and are used to evaluate the properties and reveal the active
771 processes that control the hydraulic responses of the studied system, as well
772 as the flow geometry described by the flow dimension N (Barker, 1988).
773 With these definitions, we consider the four following models: (i) the refer-
774 ence cylindrical flow model without leakage (*Model1*) corresponding to solu-
775 tion (B.3) with $N = 2$ and $1/B^2 = 0$, (ii) the generalized radial flow model
776 without leakage (*Model2*) corresponding to solution (B.3) with $1 \leq N \leq 3$,
777 $N \neq 2$ and $1/B^2 = 0$, (iii) the cylindrical flow model with leakage (*Model3*)

778 corresponding to solution (B.3) with $N = 2$ and $1/B^2 > 0$, and (iv) the
779 generalized radial flow model with leakage (*Model4*) corresponding to solu-
780 tion (B.3) without restrictions, except the cases $N = 2$ and $1/B^2 = 0$ which
781 correspond to the previous domains. For all these models, the following
782 assumptions and statements are considered:

783 (i) The ortho-radial extent b in (B.3) is set such that the exchange area
784 between the pumped borehole and the aquifer is constant and equal to that
785 for $N = 2$ and $b = 1$ m, knowing that b corresponds to the (unknown) aquifer
786 thickness in this case.

787 (ii) The correction of head data for regional trend associated with tran-
788 sient head changes is assumed to be not necessary because the long-term
789 monitoring performed during the year preceding the tests shows negligible
790 variations at the scale of the tests (decrease smaller than 0.07 mm/h).

791 (iii) The wellbore storage coefficient is *a priori* set to 10^{-12} m² for the
792 packer tests, which corresponds to a negligible pumping chamber deforma-
793 tion, while it is *a priori* set to the free surface area of the pumping well for
794 open borehole pumping tests.

795 (iv) The flowrate is assumed to be either constant or exponentially de-
796 creasing during each pump step.

797 The parameter estimation is done by considering that (i) the wellbore
798 storage coefficient S_w and the skin factor σ_w mostly impact the drawdown
799 data collected in the pumped borehole such that S_w is evaluated by fitting
800 the shape of the beginning of the corresponding curve and σ_w the amplitude
801 of this curve, and (ii) the aquifer diffusivity value K/S_s , hydraulic conduc-
802 tivity K , and leakage factor B are evaluated by fitting the response delay

803 of the observation well, the slopes of the drawdown curves collected in the
804 pumped and observation wells, and the amplitude of these curves, respec-
805 tively. When a common model reproducing the data collected in both the
806 pumped and observation boreholes cannot be found, we define a model for
807 each borehole resulting in estimated properties and parameters associated
808 with each borehole.

809 These estimations are systematically performed with the following pro-
810 cedure until obtaining a satisfying fit between the collected data and the
811 considered model. First, the standard cylindrical flow model without leak-
812 age (*Model1*) is considered and the resulting hydraulic property values are
813 used for tests comparison. Then, other flow geometries without leakage are
814 explored (*Model2*), and finally the impact of leakage is analyzed with cylin-
815 drical flow (*Model3*) and generalized radial flow (*Model4*). The best fit that
816 is obtained manually is verified, and improved if needed, with an automatic
817 fitting tool. This tool, which relies on the gradient algorithm with random
818 multistart method, is used to solve the corresponding least square problem
819 with weights applied to critical parts of the head data. In particular, addi-
820 tional weights are applied on the beginning of the drawdown curve in the
821 observation well, the end of the drawdown and recovery curves in both the
822 pumped and observation wells, as well as the end of the drawdown steps
823 when considering step-by-step flow rates. The beginning of the drawdown
824 curve in the observation well is carefully fitted because it allows to adjust
825 accurately the diffusivity value.

826 Finally, we also provide the transmissivity values estimated from Theis'
827 solution with the standard recovery interpretation method (Kruseman and

828 de Ridder, 1990) when the conditions ensuring the reliability of this solution
829 hold. These conditions, which correspond to constant pumping flow rate,
830 negligible wellbore storage and skin effects, and validity of the logarithmic
831 Jacob's approximation, are fulfilled by working on the end of well-developed
832 recovery curves. Note that the wellbore storage effect is negligible for packer
833 tests and that Theis's solution is a restriction of *Model1* to a constant flowrate
834 with no pumping well storage and no skin effect.

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