

# 1 Quantification of the specific yield in a two-layer hard-rock 2 aquifer model

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## 13 Abstract

14 Hard Rock Aquifers (HRA) have long been considered to be two-layer systems, with a mostly  
15 capacitive layer just below the surface, the saprolite layer and a mainly transmissive layer  
16 underneath, the fractured layer. Although this hydrogeological conceptual model is widely accepted  
17 today within the scientific community, it is difficult to quantify the respective storage properties of  
18 each layer with an equivalent porous medium model. Based on an HRA field site, this paper attempts  
19 to quantify in a distinct manner the respective values of the specific yield ( $S_y$ ) in the saprolite and the  
20 fractured layer, with the help of a deterministic hydrogeological model. The study site is the  
21 Plancoët migmatitic aquifer located in north-western Brittany, France, with piezometric data from 36  
22 observation wells surveyed every two weeks for eight years. Whereas most of the piezometers (26)  
23 are located where the water table lies within the saprolite, thus representing the specific yield of the  
24 unconfined layer ( $S_{y1}$ ), 10 of them are representative of the unconfined fractured layer ( $S_{y2}$ ), due to

25 their position where the saprolite is eroded or unsaturated. The two-layer model, based on field  
26 observations of the layer geometry, runs with the MODFLOW code. 81 values of the  $Sy_1/Sy_2$   
27 parameter sets were tested manually, as an inverse calibration was not able to calibrate these  
28 parameters. In order to calibrate the storage properties, a new quality-of-fit criterion called "AdVar"  
29 was also developed, equal to the mean squared deviation of the seasonal piezometric amplitude  
30 variation. Contrary to the variance, AdVar is able to select the best values for the specific yield in  
31 each layer. It is demonstrated that the saprolite layer is about 2.5 times more capacitive than the  
32 fractured layer, with  $Sy_1=10\%$  ( $7\%<Sy_1<15\%$ ) against  $Sy_2=4\%$  ( $3\%<Sy_2<5\%$ ), in this particular  
33 example.

#### 34 **Keywords**

35 Hard-rock aquifer; Specific yield; Two-layer numerical model; Quality-of-fit criterion

#### 36 **Highlights**

- 37 - Quantitative evidence that the saprolite layer is more capacitive than the fractured one
- 38 - New quality-of-fit criterion, AdVar, based on the piezometric amplitude variations

#### 39 **1 Introduction**

40 Hard-Rock aquifers (HRA) have long been considered to be two-layer systems, with (i) a weakly  
41 transmissive but rather capacitive layer (with a high specific yield) just below the surface, the  
42 unconsolidated weathered layer (also called the saprolite here, or the regolith) and (ii) a more  
43 transmissive but less capacitive layer underneath, the fractured layer. This hydrogeological  
44 conceptual model is now widely accepted in the scientific community (see for instance Chilton and  
45 Foster, 1995; Cho *et al.*, 2003; Dewandel *et al.*, 2006; Dewandel *et al.*, 2011; Lachassagne *et al.*, 2011;  
46 McFarlane, 1992; Taylor and Howard, 1999, 2000; Wright, 1992). These two layers belong to the  
47 HRA weathering profile and reach, in general, a thickness that may exceed 100 m (Lachassagne *et al.*,  
48 2011). At the watershed scale, the hydrodynamic storage and flow properties of the underlying

49 unfractured rocks (basement) are negligible. The capacitive (or storage) properties of this two-layer  
50 system, namely its storativity, or specific yield  $S_y$  where the aquifer is unconfined, were first studied  
51 and characterized to gain a better estimate of the long-term groundwater storage available in HRAs.  
52 It was established early on that the fractures in HRAs are well connected (Lenck, 1977) and later, that  
53 this fractured layer could be considered a continuous aquifer (Guihéneuf *et al.*, 2014; Lachassagne *et*  
54 *al.*, 2001). Some studies have focused on the specific yield of the saprolite layer, and consequently  
55 on the capacitive role it can play during withdrawals (Detay *et al.*, 1989; Howard and Karundu, 1992;  
56 Rushton and Weller, 1985). The processes controlling the development of these two layers are  
57 increasingly well understood and the ways to define their respective geometry and thickness are  
58 more precise (Dewandel *et al.*, 2006; Lachassagne *et al.*, 2011; Wyns *et al.*, 2004); moreover,  
59 pumping test methods to characterize their hydrodynamic properties at the borehole scale have  
60 been improved (Maréchal *et al.*, 2004). However, the precise determination of the respective  
61 storage properties of each layer remains an issue, particularly at the watershed scale (Dewandel *et*  
62 *al.*, 2012).

63 A number of authors have modelled these systems as equivalent porous media, but none of them  
64 has managed to calibrate the specific yield of both layers simultaneously. Gupta *et al.* (1985) used a  
65 single-layer model, considering that both layers were interconnected. Ahmed *et al.* (2008) presented  
66 a two-layer model calibrated on an Indian site, but unfortunately the saprolite layer was always  
67 unsaturated, which made it impossible to calibrate its specific yield. An interesting specific yield  
68 calibration for a two-layer model of an HRA is presented in Lubczynski and Gurwin (2005), but the  
69 paper did not focus on this parameter, so that the specific yield values were not presented, nor the  
70 potential differences between the saprolite and the fractured layer. The authors point out the  
71 difficulty in calibrating the specific yield with an automatic inverse method like PEST, and prefer a  
72 trial-and-error calibration, in order to "*have the best fit of the pattern of rises and recessions of the*  
73 *groundwater table*". The same kind of difficulty was also highlighted by Mazi *et al.* (2004), where to  
74 calibrate the specific yield, the authors needed the help of an expert as a complement to the

75 automatic calibration. In fact, automatic calibration methods are mainly focused on the hydraulic  
76 conductivities, adjusted with the help of a quality-of-fit criterion based on the differences between  
77 the modelled and observed hydraulic heads (Carrera *et al.*, 2005; de Marsily *et al.*, 2000; Zhou *et al.*,  
78 2014). For aquifer management purposes, a correct quantification of the distinct specific yields of  
79 the two layers is important, as a potentially highly capacitive layer represented by the saprolite may  
80 sustain the exploited water resources in the fractured layer.

81 In this context, the main objective here is to calibrate the specific yield in each of the two layers of a  
82 finite-difference hydrogeological model, at the watershed scale. This parameter, representative of  
83 the storage properties, is crucial in groundwater management purposes. Because of the difficulties  
84 mentioned above, this calibration required the development of a new quality-of-fit criterion. This  
85 study uses field data from an HRA in Brittany, France, described in the following section. The model  
86 is then presented, followed by the calibration (approach and results). The results are discussed, and  
87 a conclusion summarizes the main results of the study.

## 88 **2 Geology and hydrogeology of the study site**

### 89 **2.1 General presentation**

90 The studied site (Durand *et al.*, 2006) is located in north-eastern Brittany, France, 10 km from the  
91 English Channel shoreline (Figure 1), in a landscape of grass-land, forest and farmland, with a smooth  
92 relief. In the middle of the studied site stands a 90 m ASL hill, surrounded by the Arguenon River at  
93 10 m ASL flowing toward the English Channel (Figure 1). The migmatites that constitute the rocks in  
94 this area belong to the Saint-Malo dome, exhumed at the end of the Cadomian Orogeny (540 Ma).

95 These partially melted rocks originated from detrital sediments interbedded with graphitic cherts,  
96 composed of quartz. They now form a folded gneiss with relict bands of cherts. They were later  
97 intruded by dolerite dykes during the Hercynian period (330 Ma). The associated hard-rock aquifer is  
98 located mostly in the sub-surface stratiform weathered layers (Durand *et al.*, 2006), which consist of:  
99 (i) a cover of unconsolidated weathered rocks (saprolite), several tens of meters thick where it has

100 been preserved from erosion, consisting mainly of clay or sandy clay, that are the weakly permeable  
101 transformation products of the initial minerals; (ii) beneath this layer, and above the unweathered  
102 bedrock, a fractured layer, some 50 m thick or more, resulting from rock shattering under the  
103 influence of stress generated by the swelling of certain minerals during the early stages of  
104 weathering (Dewandel *et al.*, 2006; Lachassagne *et al.*, 2011; Wyns *et al.*, 2004). Field surveys and  
105 geophysical mapping of the two weathered-fractured layers and of the various geological  
106 heterogeneities, such as graphitic cherts and dolerite dykes, are described in a previous study  
107 (Durand *et al.*, 2006). In an area covering only 4 km<sup>2</sup>, six pumping wells and 36 piezometers (**Error!**  
108 **Reference source not found.**), owned and monitored by the Nestlé Waters Company for bottled  
109 natural mineral and spring water, provide an unusually rich set of hydrogeological data. While most  
110 piezometers (26) are located where the saprolite is saturated, and will thus help to quantify the  
111 storage in this layer, 10 of them are located where the saprolite is either eroded, or unsaturated, and  
112 will consequently help the storage quantification in the fractured layer.

113

114 *Figure 1. Location of the study area (within the grey-shaded polygon), the meteorological*  
115 *stations (stars), and the only gauging station (square)*

116

117 *Figure 2. Geometry of the finite-difference model, boundary conditions, thickness of layer 1*  
118 *(white: zero thickness) and location of the piezometers with their respective numbers*

119

## 120 **2.2 Recharge estimation**

121 The daily rainfall was measured directly at the Plancoët bottling plant (Figure 1). The mean annual  
122 rainfall (R) is on average 800 mm, with a typical oceanic climate. Around Plancoët, three weather  
123 stations belonging to Météo France, located in Pleurtuit, Quinténic and Trémour (Figure 1), also  
124 provided data on rainfall and daily potential evapotranspiration (PET) estimated with Penman's  
125 relation (Penman, 1948). Daily river flow measurements were available at the Jugon-les-Lacs gauging

126 station (Figure 1) on the Arguenon River, which drains the studied area. Over the eight years of the  
127 monitored period, a mean annual river discharge of 253 mm/y was found at the Jugon-les-Lacs  
128 gauging station, for the area of its catchment (see Durand (2005) for more details). Thornthwaite's  
129 method (Castany, 1967; Maidment, 1993; Vittecoq *et al.*, 2010) was used at a daily time step and  
130 during the eight-year monitored period to compute the effective rainfall ( $Eff_R$ ), equal to  $P$  minus Real  
131 EvapoTranspiration (RET), or to the sum of the aquifer recharge plus the surface runoff over the  
132 catchment. The computation used the rainfall data measured directly on the Plancoët site, and the  
133 weighted average of PET data from the three Météo France weather stations calculated for the site.  
134 The maximum soil storage capacity (MSC), the parameter used in Thornthwaite's method to  
135 temporarily store rainfall in the soil before it is taken up by RET and  $Eff_R$ , was calibrated so that the  
136  $Eff_R$  value would be as close as possible to the available annual catchment flow in the area. In this  
137 hydrogeological context, both runoff and aquifer recharge reach the river in a year (Molénat *et al.*,  
138 1999). Rounding off the value, the best fit for MSC was obtained with 100 mm, leading to a mean  
139 real evapotranspiration of 530 mm/y and an annual effective rainfall of 247 mm/y, quite close to the  
140 average river discharge. Figure 3 presents the meteorological data ( $P$ , RET and  $Eff_R$ ) averaged for  
141 each model time step in mm/day. It shows that  $Eff_R$  is positive only during the winter season, when  
142 RET is sufficiently low. Considering the landscape, smooth relief and grassy hills, the field  
143 observations during the winter rainy season (no runoff observed even during the most intense rainy  
144 periods), and for simplicity reasons, the recharge was fixed at 100%  $Eff_R$ . This will be discussed in the  
145 final discussion part below.

146

147 *Figure 3. Precipitation (P), calculated real evapotranspiration (RET) and effective rainfall*  
148 *(Eff<sub>R</sub>) used for each model time-step*

### 149 **2.3 Water table variations**

150 The piezometric signals in this type of aquifer, in a temperate climate, have a pseudo-sinusoidal  
151 shape with an annual period, where the highest levels are observed at the end of winter and the

152 lowest at the end of summer. The amplitude of the head variations between the high and low levels  
153 depends both on the time distribution of the recharge and on the  $S_y$  values (Maréchal *et al.*, 2006).  
154 As the specific yield plays an active role only for an unconfined layer, it is either  $S_y$  in the saprolite  
155 layer 1 ( $S_{y1}$ ) or  $S_y$  in the fractured layer 2 ( $S_{y2}$ ) that is effective, depending on the piezometer  
156 location:  $S_{y1}$  is effective where layer 1 (saprolite layer) is present and saturated (26 piezometers),  
157 and  $S_{y2}$  will be effective where layer 1 has been eroded or is unsaturated (10 piezometers). In the  
158 data set, both piezometer types are well represented, and it is interesting to compare the signals  
159 obtained for each type. The piezometric head was measured manually in each observation hole from  
160 1/1/1996 to 30/11/2003, with a time step of approximately 15 days. From these data, one can see  
161 that the mean annual amplitude variation of the piezometric levels is higher in the piezometers  
162 representing layer 2, the fractured layer ( $6.1 \pm 2.3$  m in average) than in those representing layer 1,  
163 the saprolite ( $3.4 \pm 1.3$  m in average). An example is shown in Figure 4.

164

165

166 *Figure 4. Measured water table in two types of piezometers: P17 in the fractured layer and*

167 *P26 in the saprolite*

### 168 **3 Model description**

169 The finite-difference PMWIN model (Chiang and Kinzelbach, 2000) that uses the MODFLOW code

170 (Harbaugh and McDonald, 1996) was chosen for this work. The model was built with two parallel

171 layers in order to account for the assumed distinct hydrodynamic properties of the saprolite (layer 1),

172 and the underlying weathered fractured layer (layer 2).

173 The geometry of each of these layers (shape of top and bottom) was determined by extensive field

174 work over the entire 116 km<sup>2</sup> study area (Durand *et al.*, 2006). The maximum thickness of layer 2,

175 where it is totally preserved from erosion, was found to be quite uniform across the studied area and

176 was estimated at 100 m, a thickness consistent with our experience of the Brittany geology and the

177 available borehole logs and geophysical data (Durand, 2005). Layer 2 is present over the whole  
178 modelled area (116 km<sup>2</sup>), as it has never been totally eroded, whereas layer 1, with a maximum  
179 thickness of 40 m, covers only 54 km<sup>2</sup>, due to local patches of total erosion (**Error! Reference source  
180 not found.**).

181 In the centre of the modelled area, owned by Nestlé Waters and including the bottled-water  
182 exploitation zone, the accuracy of the structural map and the number of hydrogeological data are  
183 much higher than in the other areas. The rectangular grid of the model (**Error! Reference source not  
184 found.**) is therefore a compromise between good precision where the data are dense and relatively  
185 fast calculations: consequently, the width of the rectangular model cells varies from 400 m on the  
186 borders to 40 m in the exploitation zone. Each of the two layers is modelled vertically by a single cell  
187 whose height is equal to the thickness of the corresponding layer. The layers are connected  
188 vertically, as they are assumed to be in reality. Layer 1 is modelled as an unconfined aquifer and  
189 layer 2 can be either confined or unconfined, depending on the potential lowering of the piezometric  
190 head below the bottom of layer 1.

191 The simulations were performed in a transient flow regime which allowed the time-dependent  
192 seasonal and yearly piezometric variations observed in the aquifer to be reproduced. The modelling  
193 runs from 1/1/1996 to 30/11/2003, with a time step of 15 days, similar to the frequency of the  
194 piezometric head measurements.

195 Six pumping wells in the exploitation zone (**Error! Reference source not found.**) are used for bottled-  
196 water production and their time-varying discharges are precisely recorded and used in the model.

197 No other significant pumping is known to occur in the whole modelled domain, except a few tens of  
198 litres per day, in the summer, from shallow wells, not considered in this study.

199 The total modelled domain, chosen much larger than the area exploited by the bottling plant, is  
200 limited by permanent rivers, considered to be prescribed-head boundaries, so no conductance  
201 parameter was set for these cells (**Error! Reference source not found.**). The river elevations were  
202 extracted from the 1/25 000 topographic map of the area (IGN, 2000) assuming a linear slope



203 between known points (contour lines every 5 m). In the exploitation zone, the topographic  
204 depression due to a disused quarry of graphitic cherts located near the top of a hill is at the origin of  
205 a small perennial lake (**Error! Reference source not found.**). The level of this lake, generally higher  
206 than that of the observed nearby piezometric levels, shows that it functions as an infiltration zone. It  
207 is modelled as a reservoir in the MODFLOW code (**Error! Reference source not found.**), with a  
208 prescribed constant level, a water depth of 1 m, and an underlying 1 m-thick sediment layer with a  
209 vertical hydraulic conductivity of  $1.2 \cdot 10^{-5}$  m/s. This value was calibrated so that the infiltration from  
210 the lake is consistent with its hydrological balance. Two small temporary rivers (**Error! Reference**  
211 **source not found.**) surrounding the hill are considered as drains in the model, because they drain the  
212 aquifer during high-water periods and are dry during the rest of the year. A calibrated hydraulic  
213 conductance of  $5.8 \cdot 10^{-4}$  m<sup>2</sup>/s was assigned to the contact area between the aquifer and these drains.  
214 The initial value of the piezometric heads on January 1<sup>st</sup>, 1996 was estimated as follows: a  
215 preliminary run of the model over the whole 8-year period started with heads at the ground surface;  
216 the calculated heads on November 3<sup>rd</sup>, 2003 at the end of this preliminary run were then taken as the  
217 initial conditions for January 1<sup>st</sup>, 1996.

## 218 **4 Calibration**

### 219 **4.1 Homogeneous model calibration**

220 In this type of aquifer, the hydraulic conductivity might be very heterogeneous; but the  
221 heterogeneity does not depend primarily on the geometry of the two layers, but rather on the  
222 location of fractures and other spatial discontinuities. As this type of heterogeneities was not the  
223 main focus here, a homogeneous hydraulic conductivity was chosen for each layer, and the PEST  
224 automatic calibration method in transient state (Doherty, 2004), within the PMWIN interface, was  
225 used to provide the best possible average fit. In a first approximation, the hydraulic conductivity and  
226 the specific yield, considered here to be uniform in space and identical for the two layers, were  
227 calibrated simultaneously: the best calibrated hydraulic conductivity was  $8.1 \cdot 10^{-7}$  m/s, and the

228 specific yield was 6 %. An arbitrary value of the storage coefficient for the confined layer was set at  
229  $10^{-4}$ . As the hydraulic conductivity is only roughly calibrated on the whole model, the simulated  
230 heads are therefore shifted locally, as compared to the observed ones. It is considered that this shift  
231 does not influence the further calibration of Sy1 and Sy2, based on a good amplitude variation fit.  
232 This specific point is discussed in the final discussion part of the article.

#### 233 **4.2 Classical calibration of the specific yield using the variance criterion**

234 In a second step, a model with distinct storage properties in the two layers was used to obtain a  
235 better calibration of the specific yield (Sy). This hydraulic parameter may be considered the most  
236 important one in the two-layer model. Contrary to the hydraulic conductivity, which influences the  
237 average hydraulic heads, this parameter influences primarily the amplitude of the hydraulic-head  
238 variations. We used PEST for an automatic calibration of Sy1 and Sy2, fixing the previously calibrated  
239 value for the hydraulic conductivity. Sy1 was found to be optimum at 3%, but the Sy2 calibrated  
240 values were always the maximum defined ones, even when amounting to 50%. This can be explained  
241 by the fact that, due to the imperfect calibration of the hydraulic conductivity of the model, the  
242 average simulated head values are shifted as compared to observed data, and that the quality-of-fit  
243 criterion used in PEST is the least squares of the differences between modelled and observed heads.  
244 As a high Sy tends to reduce the amplitude variation of the signal, the quality-of-fit criterion is better  
245 with a "flat" signal than a varying one in the case where the general average is very different from  
246 the true one. In order to understand the automatic calibration process, and to quantify the  
247 performance of each model, various combinations of Sy parameters were tested manually. Nine  
248 values of Sy1 and Sy2 were thus tested (1%, 2%, 3%, 4%, 5%, 6%, 7%, 10% and 15%), leading to 81  
249 model runs. The classical head squared deviation variance (Var, Equation 1) between the calculated  
250 ( $calc_d$ ) and observed heads ( $obs_d$ ) on each measurement day of the data set was calculated for all 36  
251 piezometers and this variance was averaged over the whole data set for each model.

$$252 \text{Var} = \frac{\sum_{d=1}^n [calc_d - obs_d]^2}{n} \quad (1)$$

253 with n the number of data points for each piezometer.

254 Note that in PEST, the sum of squared deviation is used, but here we take into account the number  
255 of measurements over periods of varying lengths in order to compare the results obtained for each  
256 piezometer. Considering all piezometers, the best Var value was 97 m<sup>2</sup> for Sy1=3% and Sy2=15%.  
257 Nevertheless, it appeared that these statistics might be biased by the fact that some simulated heads  
258 concerned another layer than the one of the observed data (for instance, the observed piezometry is  
259 in the saprolite while the computed one is in the fractured layer, or vice-versa). As the hydraulic  
260 conductivity was not calibrated, this was observed on 7 piezometers representative of the saprolite,  
261 and on 4 from the fractured layer. In order to avoid this specific bias and improve the results, we  
262 chose to remove these piezometers and re-calculate the average Var values. The results obtained for  
263 the various Sy values are given in matrix form (Table 1), the values of Var are shown with Sy1 values  
264 in columns and Sy2 values in rows. The minimum Var values are highlighted (corresponding to the  
265 better fit). Table 1 shows that the coloured cells are below the diagonal matrix, i.e. for Sy2>Sy1, and  
266 that the maximum chosen Sy2 value (15% here) leads to the better Var value. This confirms that, for  
267 the same reasons as explained above, the Var criterion, or any criterion based on squared head  
268 deviations, as in PEST, is not appropriate for the calibration of Sy. It is therefore necessary to  
269 develop another criterion better adapted to calibrate Sy in each layer.

270

271 *Table 1. Var values (in m<sup>2</sup>) obtained for all Sy1 and Sy2 values. Yellow: minimum values;*  
272 *orange, red and light brown respectively: classes around the minimum, with an increase of*  
273 *Var of 5% of the total variation range between two successive classes*

274

### 275 **4.3 New calibration of the specific yield taking the amplitude variation into account**

276 To better fit the specific yield, a new performance criterion, named "AdVar", was developed, based  
277 on the seasonal piezometric amplitude variations. For each piezometer, and for each available  
278 measurement on day d, a moving interval of one year after d was defined both for the observed and

279 the calculated heads. Then for that one-year interval, each piezometer amplitude-deviation variance  
 280 AdVar is defined as the average of the squared amplitude deviations, i.e.:

$$281 \text{ AdVar} = \frac{\sum_{d=1}^{n_{\text{day}}} [(\max_{\text{calcd}} - \min_{\text{calcd}}) - (\max_{\text{obsd}} - \min_{\text{obsd}})]^2}{n_{\text{day}}} \quad (2)$$

282 with  $\max_{\text{calcd}}$ ,  $\min_{\text{calcd}}$ ,  $\max_{\text{obsd}}$ ,  $\min_{\text{obsd}}$  respectively the maximum-minimum values of the calculated  
 283 and observed heads over the one-year interval after day d, and  $n_{\text{day}}$  the number of measurement  
 284 dates d available, i.e. the total number of data points less those of the last year of data. Like the  
 285 variance, AdVar is always positive and the smaller values indicate a better fit. For a better  
 286 visualisation of the AdVar behaviour compared to Var, when quantifying the fit between theoretical  
 287 sinusoidal curves, please refer to Appendix 1.

288 Considering all piezometers, the best AdVar value was 9.7 m<sup>2</sup> for Sy1=10% and Sy2=4%. Removing  
 289 the biased piezometers as previously, and re-calculating the average AdVar values, the same matrix  
 290 form as for Var was used for AdVar in 2, with Sy1 values in columns and Sy2 values in rows. 2 shows  
 291 that the coloured cells are above the diagonal matrix, i.e. for Sy1>Sy2, with AdVar, which seems  
 292 more realistic from a hydrogeological viewpoint than the results obtained with Var. Following this  
 293 criterion, the specific yield is about 10% in the saprolite (Sy1) and 2% in the fractured layer (Sy2). The  
 294 uncertainty intervals are 7%<Sy1<15% and 1%<Sy2<3%.

295  
 296 *Table 2. AdVar values (in m<sup>2</sup>) obtained for all Sy1 and Sy2 values. Yellow: minimum values;*  
 297 *orange, red and light brown respectively: classes around the minimum, with an increase of*  
 298 *AdVar of 0.5% of the total variation range between two successive classes*

299

300

#### 301 **4.4 Comparison of the simulated water tables from the best adjustments of Var and AdVar**

302 To give a better view of the results obtained in each of the two layers of the model, Figure 5 shows  
 303 the observed piezometric variations compared with two simulations in P26, a piezometer

304 representative of the saprolite layer, and in P17, representative of the fractured layer. The first  
 305 model, with  $Sy_1=2\%$  and  $Sy_2=15\%$ , corresponds to the best performance for the Var criterion, and  
 306 the second model, with  $Sy_1=10\%$  and  $Sy_2=2\%$ , to the best performance for the AdVar criterion.  
 307 Even if the hydraulic conductivity, and thus the mean value of the piezometric head is not perfectly  
 308 fitted, the second model with the lowest  $Sy_2$  and the highest  $Sy_1$  better mimics the observed  
 309 amplitude variations than the first one, with low  $Sy_1$  and high  $Sy_2$  values.  
 310 The Var and AdVar values are given in Table 3 for each of these piezometers with the two above  
 311 models. Except for Var in P17, the values follow the same trend as the average Var and AdVar  
 312 values: the first model gives a better Var, and the second a better AdVar. Between two distinct  
 313 models, an expert eye would choose in accordance with the AdVar criterion, not with the Var one.  
 314 As a conclusion to this part of the work, the obtained calibration of  $Sy$  can be considered very  
 315 satisfactory, particularly when one considers that, for this study, no spatial variations neither of the  
 316 hydraulic conductivity, nor of the specific-yield, were considered.

317

318 *Figure 5. Examples of piezometric variations for P26 within the saprolite and P17 within the*  
 319 *fractured layer. Two model results corresponding to the best Var and AdVar values are*  
 320 *compared to the observed data*

321 *Table 3. Var and AdVar values (in  $m^2$ ) for piezometers P26 and P17 with two  $Sy$  set of values*

	$Sy_1=2\%, Sy_2=15\%$		$Sy_1=10\%, Sy_2=2\%$	
	Var	AdVar	Var	AdVar
P17	16.0	22.9	13.3	1.5
P26	6.2	14.2	16.1	0.3

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## 322 5 Discussion

### 323 5.1 Comparison of specific yield values with other studies

324 These results of specific yield values are consistent with the conceptual model developed by  
325 Lachassagne *et al.* (2001) and Dewandel *et al.* (2010), notably with a decrease of  $S_y$  with depth. The  
326 obtained  $S_y$  values ( $S_{y1}=10\%$  and  $S_{y2}=4\%$  for the best AdVar values) are higher than those given by  
327 Rushton and Weller (1985) for a granite in India and by Compaore *et al.* (1997) for a granite in  
328 Burkina Faso. These authors estimated the specific yield of the saprolite layer at between 1 and 2%.  
329 Nevertheless, as shown by Wyns *et al.* (2004),  $S_y$  in the saprolite is sensitive to the type of lithology:  
330 for instance,  $S_y$  increases with the coarsening of the minerals of the parent rock and also with the  
331 quartz content. The interval of specific-yield values measured by Wyns *et al.* (2004) on several types  
332 of hard-rock lithologies in Brittany (France) includes the values estimated in the present study.

### 333 5.2 Recharge sensitivity

334 In order to simplify the results, the recharge value was fixed arbitrarily in this study, considering that  
335 runoff is negligible. Previous work done elsewhere in Brittany (Durand and Juan Torres, 1996;  
336 Jiménez-Martínez *et al.*, 2013; Molénat *et al.*, 1999) using other methods, such as isotope and  
337 natural tracer analyses, river discharge recession-curve analysis, or temporal groundwater head  
338 variations in response to recharge inputs, has arrived at similar conclusions. Nevertheless, it is  
339 possible to explore the sensitivity of the model to the recharge, testing various recharge values.  
340 Figure 6 shows the observed and simulated heads at P26, for the reference model ( $S_{y1}=10\%$ ,  
341  $S_{y2}=4\%$ , Recharge= $100\% \text{ Eff}_R$ ), and for two other models, keeping the same  $S_y$  values, and testing  
342 Recharge= $70\% \text{ Eff}_R$  and Recharge= $30\% \text{ Eff}_R$ . Note that the simulated heads with low recharge values  
343 never stop decreasing from the beginning to the end of the simulation, and even drop below the  
344 observed values. They also decrease a little with the maximum recharge, due to a problem in the  
345 initial head, difficult to calibrate here, but it appears that the average heads tend to stabilize at the  
346 end of the modelled period. It is not the case with lower recharge values, leading to the conclusion  
347 that these values are too low to provide enough water to the aquifer, compared to the real natural

348 discharge and pumping rate on the site. Some graphics showing the Var and AdVar results with a  
349 complete parameter set (8 recharge values for each Sy combination) are presented in Appendix 2.

350

351 *Figure 6. Observed and modelled heads for P26, testing various recharge values*

### 352 **5.3 Hydraulic conductivity sensitivity**

353 In this study, an arbitrary choice was made to leave out the hydraulic conductivity calibration.

354 Although it is the main parameter of the flow budget within the aquifer, this choice was made in

355 order to focus attention on the storage parameter, a crucial parameter in HRA to quantify the

356 exploitable water resources. The aim was to quantify the specific-yield in the two layers of an HRA,

357 highlighting their differences, and not to build a fully calibrated model for water-resource

358 management purposes. A local adjustment of hydraulic conductivities may induce some minor

359 modification of the temporal head amplitude variations. This is shown in Figure 7 with the example

360 of P26: the reference model (black plain line), with  $K=8.1 \cdot 10^{-7}$  m/s, is compared to models with  $K=8.1$

361  $10^{-6}$  m/s (light grey) and  $K=1.2 \cdot 10^{-7}$  m/s (dark grey). Changes of K highly influence the mean

362 interannual piezometric values, but influence in a minimal way the amplitude variations. One can

363 conclude that more reasonable changes in K than those of this sensitivity analysis, to better fit the

364 local data, would not seriously impact the amplitude variations. It is considered that, in the high-

365 density data zone where the piezometers are located, the amplitude variations would not be much

366 affected, as the chosen homogenous K value is already quite well fitted. It is possible, however, that

367 the calibrated Sy values for both layers might not be quite exact, due to the local K variations. But

368 the general tendency toward a higher storage capacity in the saprolite layer than in the fractured one

369 will stay the same, whatever the local K values.

370

371

372 *Figure 7. Observed and modelled heads on P26, testing various K values*

373

---

**374 5.4 Synthesis**

375 Figure 8 synthesises these results in a qualitative way, presenting the respective behaviours of the  
376 saprolite and the fractured layer in two columns. In the case where the water table stays in the  
377 saprolite layer (first column), the observed water table (dotted blue line) varies with a low amplitude.  
378 The model M1 (in orange), with a high specific yield, well reproduces this low amplitude variation,  
379 but presents a computed average head value different from the observed one (lower here), as a  
380 consequence of the imperfect K calibration. Therefore, the variance calculated between the M1  
381 computed red curve and the observed data is high, whereas the AdVar criterion is very good. Still in  
382 the first column, the inverse is shown for the model M2 (in green), with a low specific yield: its  
383 amplitude variation is too high compared to the observed data, leading to a high AdVar criterion. But  
384 as M2 presents an average value very similar to the observed data, the variance is better than for  
385 M1. This first column shows a higher efficiency of the Advar quality-of-fit criterion (rather than the  
386 Variance) in identifying the best  $S_y$  (here M1 with a high  $S_y$ ), even if the average head is not well  
387 calibrated (for instance because of a locally imperfect calibration of K). Inversely, in the case where  
388 the water table stays in the fractured rock (second column), the observed water table varies with a  
389 high amplitude. The same M1 model as previously, well fitted for the average head, shows here a  
390 good variance criterion, but a weak AdVar criterion. And the same M2 model as previously, with a  
391 distinct average head but an amplitude variation similar to the data, shows a weak variance but a  
392 good Advar criterion. Again, this second column shows a greater efficiency of the Advar quality-of-fit  
393 criterion in identifying the best  $S_y$  (here M2 with a low  $S_y$ ). This emphasises that the ideal model  
394 combines M1 and M2, with a relatively high specific yield in the saprolite layer, and a lower specific  
395 yield in the fractured layer, which are the two main conclusions of this paper. Moreover, the AdVar  
396 criterion is better adapted to quantifying the amplitude variation (thus to fit the specific yield) than  
397 the Var criterion.

398

399



400 *Figure 8. Schematic view of the main results showing the observed and simulated piezometric*  
401 *amplitude variation for the two cases of a water table in the saprolite and in the fractured*  
402 *layer.*

403

## 404 **6 Conclusion**

405 In this study, a hard-rock aquifer system in Britany (France) was simulated with a two-layer  
406 deterministic hydrogeological model at the catchment scale, each layer representing a specific  
407 weathering horizon (saprolite and fractured layer). The storage capacities of each layer can be  
408 quantified thanks to a rich data set, with piezometers representing the two types of layers, when  
409 unconfined. The specific yield values are calibrated using a new quality-of-fit criterion, AdVar, based  
410 on the seasonal piezometric amplitude variations. The saprolite layer is proved to be more capacitive  
411 than the fractured layer, with a calibrated specific yield 2.5 times greater than that of the fractured  
412 layer:  $Sy_1=10\%$  ( $7\%<Sy_1<15\%$ ) against  $Sy_2=4\%$  ( $3\%<Sy_2<5\%$ ), in this particular example.

## 413 **Aknowlegdment**

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**Appendix 1**

537 In order to validate this new AdVar criterion, the respective behaviours of Var and AdVar were  
538 compared on a theoretical example. Perfect sinusoidal curves of heads (h) as a function of time in  
539 days (d) with different amplitudes were compared. From the equation of a sinusoid (Equation 3), a  
540 reference curve was calculated with an amplitude (a) of 10 m and a mean value (m) of 0 m, to act as  
541 the "observed data".

$$542 \quad h = a \cdot \sin\left(\frac{2\pi}{P} d\right) + m \quad (3)$$

543 The period (P) was fixed at 365.25 days to follow an annual variation, and the total duration was set  
544 at 30 years. This reference curve was then compared to various "model" curves, with varying m and  
545 a. The "m" parameter varied between 0 and 10 m, and the "a" parameter between 0 and 20 m.  
546 With m=0 and a=10, the model curve is identical to the reference curve, and the quality-of-fit-  
547 criterion should be equal to zero, both for AdVar and for Var. The distinct behaviours of Var and  
548 AdVar with varying "m" and "a" are shown in Figure 9.

549

550 *Figure 9. Var (grey line) and AdVar (black line) values obtained by comparing perfect*  
551 *sinusoidal shapes to a reference sinusoidal curve with a zero mean (m) and an amplitude (a)*  
552 *of 10 m. Results are shown as a function of "a" from 0 to 20 (first line) and of "m" from 0 to*  
553 *10 (second line), changing the values of "m" (first line) and of "a" (second line) in each*  
554 *column*

555

556 It is clear that AdVar is sensitive only to a variation of "a", not of "m", which is due to the way this  
557 criterion has been defined, as it depends only on the amplitude variation, which is particularly useful  
558 for the purpose of our research. On the contrary, Var depends on both parameters: whereas the  
559 minimum Var value increases with "m", the AdVar minimum value is always zero when "a" is equal to  
560 the observed one. Furthermore, the AdVar values are much more variable when "a" varies than the

---

561 Var values: on the first plot with  $m=0$ , AdVar varies between 0 and 400 as "a" varies between 0 and  
562 20, and Var between 0 and 50. This shows the advantage of AdVar with respect to Var: it is more  
563 precise on amplitude variations than Var. When all values of Var and AdVar are averaged over the  
564 total number of piezometers for each model, it is easier to compare two distinct models when these  
565 quality-of-fit values are clearly distinct from one model to another.

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**Appendix 2**

568 The results of the two quality-of-fit criteria for the 36 piezometers (average Var and AdVar values for  
569 each simulation) are presented exhaustively: Figure 10 and Figure 11, show the evolution of Var (first  
570 line) and AdVar (second line) as a function of Rech (Figure 10) and Sy2 (Figure 11). Each column  
571 corresponds to a distinct value of Sy1 and each curve to a distinct value of Sy2 (Figure 10) and Rech  
572 (Figure 11). The scale of the Y axis is chosen identical for all Var, and for all Advar, thus some curves  
573 that are too high for the scale disappear from the plots: the focus is on low criterion values.  
574 Note that the lowest Var and AdVar values are obtained mostly for the highest recharge (Rech)  
575 parameter.

576 For Var, the curve shapes in Figure 10 are very similar, generally showing a better fit towards the high  
577 recharge values and for the highest Sy2. For Sy1 up to 3 %, the best fit is obtained for a recharge of  
578 100 % Eff<sub>R</sub>, but for higher Sy1 values, this recharge is lower and varies between 80 and 100 % Eff<sub>R</sub>.  
579 For AdVar, the analysis is more delicate, as the Sy2 curves in Figure 10 do not show a homogeneous  
580 behaviour. For Sy1 up to 3 %, the lowest AdVar values are obtained for the lowest recharge. On the  
581 contrary, when Sy1 increases, except for the lowest Sy2 values, most of the lowest AdVar values are  
582 obtained with the maximum recharge, and here the difference between 80, 90 and 100 % Eff<sub>R</sub> is  
583 greater than for Var.

584

585 Figure 11 shows distinct behaviours for Var and AdVar as functions of Sy2. Judging by the Var  
586 criterion only, one might conclude that the best fit would be obtained with the highest values of Sy2,  
587 even above 15 %, as shown in section 4.3. With the AdVar criterion however, the best fit for Sy2 is  
588 between 4 and 5 %, which, although quite high for a fractured layer, is more realistic.

589

590 *Figure 10. Results of the quality-of-fit criteria Var and AdVar as functions of the recharge*  
591 *values on the X axis, each curve representing a distinct Sy2 value, and each column a distinct*  
592 *Sy1 value*



---

593

594 *Figure 11. Results of the quality-of-fit criteria Var and AdVar as functions of the Sy2 values on*  
595 *the X axis, each curve representing a distinct recharge value, and each column a distinct Sy1*  
596 *value*

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598 **Figures**

599 *Figure 12. Location of the study area (within the grey-shaded polygon), the meteorological*  
600 *stations (stars), and the only gauging station (square)*

601  
602 *Figure 13. Geometry of the finite-difference model, boundary conditions, thickness of layer 1*  
603 *(white: zero thickness) and location of the piezometers with their respective numbers*

604  
605 *Figure 14. Precipitation (P), calculated real evapotranspiration (RET) and effective rainfall*  
606 *(Eff<sub>R</sub>) used for each model time-step*

607  
608 *Figure 15. Measured water table in two types of piezometers: P17 in the fractured layer and*  
609 *P26 in the saprolite*

610  
611 *Figure 16. Examples of piezometric variations for P26 within the saprolite and P17 within the*  
612 *fractured layer. Two model results corresponding to the best Var and AdVar values are*  
613 *compared to the observed data*

614  
615 *Figure 17. Observed and modelled heads for P26, testing various recharge values*

616  
617 *Figure 18. Observed and modelled heads on P26, testing various K values*

618  
619 *Figure 19. Schematic view of the main results showing the observed and simulated*  
620 *piezometric amplitude variation for the two cases of a water table in the saprolite and in the*  
621 *fractured layer.*

622

623 *Figure 20. Var (grey line) and AdVar (black line) values obtained by comparing perfect*  
624 *sinusoidal shapes to a reference sinusoidal curve with a zero mean (m) and an amplitude (a)*  
625 *of 10 m. Results are shown as a function of "a" from 0 to 20 (first line) and of "m" from 0 to*  
626 *10 (second line), changing the values of "m" (first line) and of "a" (second line) in each*  
627 *column*

628  
629 *Figure 21. Results of the quality-of-fit criteria Var and AdVar as functions of the recharge*  
630 *values on the X axis, each curve representing a distinct Sy2 value, and each column a distinct*  
631 *Sy1 value*

632  
633 *Figure 22. Results of the quality-of-fit criteria Var and AdVar as functions of the Sy2 values on*  
634 *the X axis, each curve representing a distinct recharge value, and each column a distinct Sy1*  
635 *value*

636

#### 637 **Tables**

638 *Table 4. Var values (in m<sup>2</sup>) obtained for all Sy1 and Sy2 values. Yellow: minimum values;*  
639 *orange, red and light brown respectively: classes around the minimum, with an increase of*  
640 *Var of 5% of the total variation range between two successive classes*

641

642 *Table 5. AdVar values (in m<sup>2</sup>) obtained for all Sy1 and Sy2 values. Yellow: minimum values;*  
643 *orange, red and light brown respectively: classes around the minimum, with an increase of*  
644 *AdVar of 0.5% of the total variation range between two successive classes*

645

646 *Table 6. Var and AdVar values (in m<sup>2</sup>) for piezometers P26 and P17 with two Sy set of values*

Sy1

	1%	2%	3%	4%	5%	6%	7%	10%	15%
1%	116	95	90	90	94	99	106	128	161
2%	105	89	85	86	91	97	104	127	161
3%	99	85	82	85	90	96	103	126	161
4%	95	82	80	83	89	95	103	126	161
5%	92	80	79	82	88	95	102	126	161
6%	90	79	78	81	87	94	102	126	161
7%	88	77	77	80	86	94	101	126	161
10%	83	73	74	78	85	92	101	125	161
15%	78	69	70	75	83	91	99	125	161

647  
648

	1%	2%	3%	4%	5%	6%	7%	10%	15%
1%	166.2	63.6	35.1	23.5	17.6	14.1	12.0	9.2	8.3
2%	118.3	41.3	22.1	15.0	11.7	9.9	9.0	7.9	8.2
3%	101.2	34.5	18.5	12.8	10.3	9.1	8.5	8.1	8.8
4%	93.0	31.7	17.3	12.3	10.2	9.2	8.7	8.6	9.4
5%	88.6	30.5	16.9	12.3	10.4	9.5	9.1	9.1	10.0
6%	86.2	30.0	16.9	12.5	10.7	9.9	9.5	9.5	10.5
7%	84.8	29.9	17.1	12.7	11.0	10.2	9.9	10.0	10.9
10%	83.4	30.1	17.7	13.5	11.9	11.2	10.9	11.0	11.9
15%	83.9	30.9	18.6	14.4	12.8	12.2	11.9	12.1	12.9

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651 **Highlights**

652 - Quantitative evidence that the saprolite layer is more capacitive than the fractured one

653 - New quality-of-fit criterion, AdVar, based on the piezometric amplitude variations

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ACCEPTED MANUSCRIPT