Quantification of the specific yield in a two-layer hard-rock 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 (Sy) 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 (Sy1), 10 of them are representative of the unconfined fractured layer (Sy2), due to

1

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 Sy1/Sy2

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 Sy1=10% (7%<Sy1<15%) against Sy2=4% (3%<Sy2<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 Sy 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 unfortunatly 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 km², 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 Trémeur (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 EffR 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$_R$) 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 Sy values (Maréchal *et al.*, 2006).

154   As the specific yield plays an active role only for an unconfined layer, it is either Sy in the saprolite

155   layer 1 (Sy1) or Sy in the fractured layer 2 (Sy2) that is effective, depending on the piezometer

156   location: Sy1 is effective where layer 1 (saprolite layer) is present and saturated (26 piezometers),

157   and Sy2 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 ± 2.3 m in average) than in those representing layer 1,

163   the saprolite (3.4 ± 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 km² 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 km²), as it has never been totally eroded, whereas layer 1, with a maximum

179 thickness of 40 m, covers only 54 km², 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 1.2×10^{-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 5.8×10^{-4} m^2/s was assigned to the contact area between the aquifer and these drains.

214   The initial value of the piezometric heads on January 1st, 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 3rd, 2003 at the end of this preliminary run were then taken as the

217   initial conditions for January 1st, 1996.

4   Calibration

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 8.1×10^{-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.

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    $Var = \dfrac{\sum_{d=1}^{n}[calc_d - obs_d]^2}{n}$ (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 m² 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 m²) 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 $AdVar = \dfrac{\sum_{d=1}^{n_{day}}\left[\left(max_{calc_d}-min_{calc_d}\right)-\left(max_{obs_d}-min_{obs_d}\right)\right]^2}{n_{day}}$ (2)

282 with max_{calc_d}, min_{calc_d}, max_{obs_d}, min_{obs_d} respectively the maximum-minimum values of the calculated

283 and observed heads over the one-year interval after day d, and n_{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 m² 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 m²) 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 Sy1=2% and Sy2=15%, corresponds to the best performance for the Var criterion, and

306   the second model, with Sy1=10% and Sy2=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 Sy2 and the highest Sy1 better mimics the observed

309   amplitude variations than the first one, with low Sy1 and high Sy2 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 m²) for piezometers P26 and P17 with two Sy set of values*

	Sy1=2%, Sy2=15%		Sy1=10%, Sy2=2%	
	Var	AdVar	Var	AdVar
P17	16.0	22.9	13.3	1.5
P26	6.2	14.2	16.1	0.3

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 Sy with depth. The

326 obtained Sy values (Sy1=10% and Sy2=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), Sy in the saprolite is sensitive to the type of lithology:

330 for instance, Sy 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-Martinez *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 (Sy1=10%,

341 Sy2=4%, Recharge=100% Eff_R), and for two other models, keeping the same Sy values, and testing

342 Recharge=70% Eff_R and Recharge=30% 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 10^{-7} m/s, is compared to models with K=8.1

361   10^{-6} m/s (light grey) and K=1.2 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 Sy (here M1 with a high Sy), 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 Sy (here M2 with a low Sy). 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

16

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

6   Conclusion

In this study, a hard-rock aquifer system in Britany (France) was simulated with a two-layer deterministic hydrogeological model at the catchment scale, each layer representing a specific weathering horizon (saprolite and fractured layer). The storage capacities of each layer can be quantified thanks to a rich data set, with piezometers representing the two types of layers, when unconfined. The specific yield values are calibrated using a new quality-of-fit criterion, AdVar, based on the seasonal piezometric amplitude variations. The saprolite layer is proved to be more capacitive than the fractured layer, with a calibrated specific yield 2.5 times greater than that of the fractured layer: $Sy1=10\%$ ($7\%<Sy1<15\%$) against $Sy2=4\%$ ($3\%<Sy2<5\%$), in this particular example.

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533

534

535

536 **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 $h = a.\sin\left(\frac{2\pi}{P}d\right) + m$ \qquad (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.

566

567 **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$_R$, but for higher Sy1 values, this recharge is lower and varies between 80 and 100 % Eff$_R$.

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$_R$ 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*

597

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_R) 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 m²) 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 m²) 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 m²) 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

28

	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

649
650

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

654

655