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## HYDROL 123936

Coupling hydrodynamic, geochemical and isotopic approaches to  
evaluate oxbow connection degree to the main stream and to  
adjunct alluvial aquifer

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## 1 **1. Introduction**

2 Wetlands were subject of various scientific considerations  
3 in recent decades and benefit from specific international  
4 convention especially as waterfowl habitat (Ramsar  
5 Convention, 1971). They are indeed particularly recognized to  
6 preserve the ecological function of hydrosystems (ecological  
7 niches, refuge areas...). However, during the last decades, the  
8 general intensification of pollution has led to the  
9 contamination of most of the water bodies with negative  
10 effects on aquatic ecosystems, human health, productive  
11 activities, water system reliability and operating costs for  
12 water use (Gleick, 1998; Bates et al., 2008; Hulton, 2012;  
13 Sutton et al., 2013; UNEP, 2016). In the meantime, a world loss  
14 of about 64 to 71 % of natural wetlands is to deplore since  
15 1900 because of human activities (Davidson, 2014). Locally,  
16 some sectors are especially affected with for instance  
17 percentage of wetlands lost reaching 91% for the California  
18 State between the 1780's to the 1980's (Dahl, T.E., 1990).  
19 Actions have been therefore implemented in order: 1) to  
20 preserve or restore wetlands, 2) to complete the knowledge  
21 on their functioning and 3) to communicate about the  
22 necessity of maintaining such environments. These are the  
23 objectives, for instance, of the 3<sup>rd</sup> National Action Plan for

24 Wetlands in France (PNMH, 2014) and of the United States  
25 Geological Survey (Fretwell et al. 1996).

26 As a special feature of wetlands, oxbows are generated by  
27 spatial and temporal dynamics of rivers within their  
28 floodplains. That kind of perfluvial environments are of a  
29 major ecological importance for the habitat and diversity of  
30 fauna and vegetation. Oxbows indeed promote reproduction  
31 and provide refuge areas for biotic communities, especially  
32 fishes (Bornette et al., 1998; Ghosh and Biswas, 2017; Yang et  
33 al., 2018). However, since an oxbow is a floodplain annex, it  
34 can be supplied by local precipitation, main stream's water,  
35 alluvial groundwater from the bank between the river and the  
36 oxbow and from the bank delineating the alluvial plain (Rollet  
37 et al., 2005). Therefore, the whole ecosystem of oxbows  
38 depends largely on hydrodynamic conditions and more  
39 peculiarly on the mixing between water masses through  
40 hydrological connectivity to the main stream and/or the  
41 alluvial groundwater (Dahm et al., 1998; Amoros and Bornette,  
42 2002). It is now widely recognized that maintaining oxbows in  
43 riparian areas contributes to control floods occurrence, to  
44 stabilize river base flows during dry periods, to enhance the  
45 water quality (by nutrient retention) and to preserve  
46 ecosystems (Winter et al., 1998; Alard et al., 2001; Bullock and

47 Acreman, 2003; Larocque et al., 2016). However, obtain a  
48 complete hydrological knowledge about oxbows' dynamic  
49 remains challenging. Various monodisciplinary approaches  
50 implying mostly hydrodynamic but also hydrochemistry (Carrel  
51 and Juget, 1987; Bengen et al., 1992; Le Coz, 2003; Babka et  
52 al., 2011; Hudson et al., 2012) have been tested separately.  
53 However, such focused investigations can lead to neglect or  
54 underestimate contributions of connected water masses to  
55 the whole functioning of the oxbow which may produce  
56 unaccurate conceptual models to water managers.  
57 Multidisciplinary approach carried out on a representative and  
58 spatially distributed sampling network (boreholes and surface  
59 water points), covering both the selected wetland and the  
60 connected water masses of the whole hydrosystem, constitute  
61 an integrated solution to insure the most complete  
62 hydrological understanding of the system and therefore  
63 contribute effectively to wetlands and rivers preservation  
64 actions (restoration, rehabilitation, remeandering...).

65 The present study is carried out on the Auzon Oxbow, one  
66 of the fluvial annexes of the Allier River (Massif Central,  
67 France, Figure 1a), located in the upper Allier River basin.  
68 Ecological concerns surround that specific oxbow especially  
69 since it constitutes trout's reproduction and refuge areas.

70 Consequently, local fishing associations carried out  
71 conservation operation as the dredging of alluvial plugs to  
72 maintain its connectivity to the main stream (Beauger et al.,  
73 2015). As an experimental site of the SOAHAL Observatory  
74 (Système d'Observation d'une Annexe Hydraulique de l'Allier),  
75 a complete monitoring of the hydrosystem, including surface  
76 and groundwater with a dense spatial resolution (20 sampling  
77 sites for 0.4 km<sup>2</sup>) has been organized from 2014. The  
78 objectives are to provide effective diagnostic tools to evaluate  
79 the connection degree of the Auzon Oxbow to the Allier River,  
80 the main stream, and to the adjunct alluvial aquifer and thus  
81 to establish a complete hydrodynamic description of the  
82 Auzon Oxbow hydrosystem. To achieve that goal, the strategy  
83 was to combine individual investigation approaches through a  
84 multidisciplinary analysis on both hydrodynamic and  
85 hydrochemistry.

## 86 **2. Study area**

### 87 **2.1. General settings**

88 The study was performed on the Auzon Oxbow  
89 (sexagesimal GPS standard longitude/latitude coordinates at  
90 the confluence: 03°21'41''E/45°22'05''N; elevation: 400 m), a  
91 fluvial annex of the Allier River, a gravel bed meandering  
92 stream located about 60 km southeast of Clermont-Ferrand,

93 France. The Allier River originates at La Maure de Gardille  
94 (1423 m.a.s.l) and joins the Loire River at the Bec d'Allier near  
95 Nevers, after 410 km of course from South towards North  
96 within a 14,310 km<sup>2</sup> watershed (Figure 1a). Allier River  
97 discharge at the station K2430810 of Agnat (Pont d'Auzon),  
98 located downstream of the study area at about 1500 m to the  
99 north (03°21'26''E/45°23'09''N; elevation: 360 m), ranges from  
100 9.7 to 246.0 m<sup>3</sup>.s<sup>-1</sup> with an annual average at 30.3 m<sup>3</sup>.s<sup>-1</sup>  
101 (calculated over 26 years data; ("Banque Hydro," n.d.)). The  
102 Auzon Oxbow is located in the first alluvial plain encountered  
103 downstream of the Allier Gorges. The study area presents a  
104 temperate continental climate with relatively hot summers  
105 (mean air temperatures up to 24°C in July) and cold winters  
106 (mean temperatures around -3°C in February; "Météo-France"  
107 n.d. ). Annual precipitation is moderate within the Allier basin  
108 (692 mm on average), the valley being in a shelter position  
109 behind the western Massif Central where Atlantic humid air  
110 masses produce orographic rainfall; most of the events occur  
111 between May and October (423 mm in cumulative  
112 precipitation; "Météo-France" n.d.). Mountainous areas of the  
113 upper Allier catchment are more humid with a total  
114 precipitation around 2000 mm; minima are registered in the  
115 low Allier plain and account for around 570 mm/yr  
116 (Mohammed et al., 2014).

117 Geologically, the drainage basin of the Allier River is composed  
118 of 80% by crystalline formations (Hercynian crystalline bedrock  
119 and Cenozoic volcanic rocks), the remaining part of the  
120 watershed is made of calcareous Oligocene fluvio-lacustrine  
121 sediments (Korobova et al., 1997). The study area is located in  
122 the small subsidence basin of Brioude. That tectonic  
123 depression constitutes the western end of an E-W direction  
124 extension grabens network due to the tectonic phase in  
125 distention which took place in Western Europe during the  
126 Cenozoic period (Vanderhaeghe and Prognon, 2012). The  
127 Brioude basement is composed of a Hercynian metamorphic  
128 and magmatic bedrock overlaid by the sedimentary formation  
129 of Limagne: during the Oligocene and Miocene periods,  
130 detrital sedimentation in continental environment (alternation  
131 of clays, sands and marls with some carbonates levels) filled  
132 the basin. Since Quaternary, the alluvial deposits of the Allier  
133 River are completing the sequence on the underlying  
134 Oligocene marls (Lasnier and Marchand, 1982; Korobova et al.,  
135 1997); they extend over a width of between 0.5 and 2 km and  
136 a thickness of about 10 m at the Auzon Oxbow site (alluvial  
137 plain of Figure 1b). Due to their good hydrodynamic properties  
138 (Transmissivity =  $10^{-3}$  à  $10^{-4}$  m<sup>2</sup>/s, Storage coefficient = 8 to  
139 10%) and hydrochemical characteristics (moderate  
140 concentration, neutral pH and calcium-bicarbonate water-

141 type) (Mohammed, 2014; Mohammed et al., 2014), the  
142 alluvial aquifer of the Allier River is one of the major water  
143 resources of the area. This aquifer is therefore intensively  
144 exploited for drinking water supply and agricultural purposes  
145 as it is the case on the study site.

146

147 **Figure 1**

148

149 Thanks to its geomorphology and location, Auzon Oxbow is  
150 considered as an active floodplain oxbow (Babka et al., 2011).  
151 It was formed by the migration of an old channel of the Allier  
152 River, which occurred during two flood events in 1988 and  
153 1989. A former gravel pit located in the point bar has  
154 facilitated the cutoff process leading to the main channel  
155 abandon. Upper part of the channel was rapidly in-filled by  
156 sands and gravels; since then, only the downstream end  
157 remains connected to the main stream (Beauger, 2008)  
158 conferring to the Auzon Oxbow the first stage of development  
159 of oxbows (Gagliano and Howard, 1984; Wren et al., 2008;  
160 Hudson et al., 2012). As so, it can be supplied by water of four  
161 different origins: local precipitation, main stream's water  
162 through the confluence, groundwater inflowing from the bank  
163 between Allier River and the oxbow and finally, groundwater  
164 from the bank delineating the alluvial plain (Rollet et al.,

165 2005). The 560 m length of the oxbow can be divided into  
166 three geomorphological parts (Figure 1c):

167 - i) the upstream zone (UZ), which is disconnected from  
168 the main stream and is similar to a pond (197 m length,  
169 13 m width and maximum depth of 1.8 m) ;

170 - ii) the intermediate zone (IZ), which is a former  
171 geomorphological riffle (176 m length, 0.3 to 8 m width  
172 and maximum depth of 0.4 m) ;

173 - iii) and the downstream zone (DZ), which is connected  
174 to the Allier River by its downstream extremity  
175 (Beauger et al., 2015) (188 m length, 17 m width and  
176 maximum depth of 1.6 m).

177 Highly subject to flooding, the right bank (RB) is used for  
178 punctual grazing while the left bank (LB) is a low terrace  
179 dedicated to cereals production. However, close to the Auzon  
180 Oxbow, crops are smaller and agricultural practices relatively  
181 soft compared to the western plateau where they are much  
182 more intensive (Figure 1b). That neighboring plateau presents  
183 an aquifer that is assumed to partly feed the LB alluvial  
184 groundwater. Auzon Oxbow has been monitored since 2007  
185 (Beauger, 2008) in terms of geomorphology, sedimentation  
186 and ecology (study of diatom, macrophyte and benthic

187 macroinvertebrate communities). To complete ecological  
188 investigations, the monitoring has been extended to surface  
189 and groundwater hydrodynamic and hydrochemistry. In this  
190 purpose, near-surface piezometers (from 0.92 to 1.85 m deep)  
191 were built on the oxbow's shore of both banks (Figure 1c) in  
192 2012 (Beauger et al., 2015) as well as deep observation  
193 boreholes catching the whole aquifer thickness in 2014.

## 194 **2.2. Sampling sites**

195 Precipitation height have been collected from Météo-  
196 France database at Sainte-Florine, the closest weather station,  
197 located 4 km north-west (03°19'00"E/45°24'00"N; elevation:  
198 450 m; station 43185001) and at Naussac  
199 (03°49'42"E/44°44'54"N; elevation: 967 m; station 48105001),  
200 weather station characterizing the upper part of the Allier  
201 watershed. Allier River daily discharge is taken from the Agnat-  
202 Pont d'Auzon station ("Banque Hydro," n.d.).

203 In addition, monthly monitoring is performed at the  
204 following sites in the area (Figure 1): i) 6 surface water  
205 observation points distributed along the entire Auzon Oxbow  
206 from its upstream to its downstream ends (B2 to B7); ii) 1  
207 surface water observation point in the Allier River (Allier); iii) 6  
208 observation boreholes (10 m deep covering the entire alluvial  
209 aquifer thickness), 2 drilled in the Right Bank (RB: PZ1 and PZ2)

210 and 4 in the Left Bank (LB: PZ3 to PZ6); iv) 7 near-surface  
211 piezometers (0.85 to 1.92 m deep), located next to the oxbow  
212 on both RB and LB (P2 to P9); v) Le Monteil spring (Figure 1b)  
213 draining the neighboring plateau aquifer, which is assumed to  
214 partly feed the alluvial groundwater.

215

### 216 **3. Sampling and analytical methods**

#### 217 **3.1. Hydrodynamic monitoring [07/22/2014 – 11/24/2017]**

218 In order to assess the hydrodynamic behavior of the  
219 oxbow, the potential water sources entering the system have  
220 been investigated in terms of hydrodynamic and  
221 hydrochemistry. Surface water level of the Allier River at the  
222 confluence with the Auzon Oxbow and water table in the 6  
223 observation boreholes have been recorded on an hourly basis  
224 with an in situ Level Troll 500 probe. All water level data have  
225 been corrected from the barometric pressure variations. The  
226 hydrological station was located on LB prior to the 11/05/2015  
227 (A1, Figure 1c) and then moved to RB (A2, Figure 1c) because  
228 of a too important erosion of the left bank during previous  
229 floods. Geographical coordinates and elevation of each  
230 pressure sensor were measured using the centimetric Trimble  
231 R10 DGPS whose data was post-processed with Trimble

232 Business Center software (version 3.8.) and adjusted according  
233 to the dimensions of the boreholes in order to calculate level  
234 variations through time in the same reference of altitude  
235 (Cunningham and Schalk, 2011). The reliability of the  
236 continuous piezometric levels monitoring was checked and  
237 validated through manual measurements carried out during  
238 the 40 sampling campaigns: correlation coefficients between  
239 data recorded and manually measured ( $r^2$  from 0.92 to 0.99)  
240 testify for a good representativeness of the piezometric level  
241 time-series.

### 242 **3.2. Water chemistry monitoring**

243 Forty sampling campaigns have been performed on the 21  
244 sampling sites on a monthly basis from July 2014 to November  
245 2017, except in February 2017 when the alluvial plain was  
246 flooded. A few data are also missing for P7, because of small  
247 floods or vandalism. Prior to sampling, bottles have been  
248 rinsed two times by using the water to be sampled. Surface  
249 waters and Le Monteil spring were directly sampled using  
250 sampling vials. Groundwater was sampled using a Cole Parmer  
251 Masterflex I/S pump for near-surface piezometers, while it was  
252 a 12 V standard PVC narrow diameter submersible pump for  
253 the observation boreholes. For each groundwater sampling,  
254 stagnating water present into the borehole was renewed

255 before sampling and measuring. An intensive campaign was  
256 performed on the 23<sup>rd</sup> of November 2017 in the Auzon Oxbow  
257 in order to assess spatial distribution of electrical conductivity  
258 (EC): 124 measures have been performed in the near surface  
259 of the oxbow (0.2 m depth) along the UZ, the IZ and on the  
260 upper part of the DZ, using a WTW multi 340i and a DGPS  
261 Trimble Geo7x whose data were post-processed with  
262 Pathfinder software. Two sites of the EC campaign (Points 3  
263 and 103) were also sampled for major ions analyses. EC, pH  
264 and temperature have been measured in situ using a WTW  
265 multi 340i.  $\text{HCO}_3^-$  concentrations have been determined  
266 directly in the field by using HACH Digital Titrator, sulfuric acid  
267 (0.1600 N and 1.600 N) and Bromocresol Green-Methyl Red  
268 Indicator (Hach method 8203).

269 A total of 837 water samples have thus been taken in clean  
270 sterile polypropylene straight containers with polyethylene  
271 caps of 180 mL, transported in cooler to GEOLAB laboratory in  
272 Clermont-Ferrand (CNRS UMR 6042, University Clermont-  
273 Auvergne) and then stored at 4°C. Anions and cations were  
274 analyzed within 3 days in GEOLAB Laboratory: anions ( $\text{F}^-$ ,  $\text{Cl}^-$   
275  $\text{NO}_2^-$ ,  $\text{NO}_3^-$ ,  $\text{PO}_4^{3-}$ ,  $\text{SO}_4^{2-}$ ) using the Thermo Fisher Scientific  
276 Dionex DX120 ionic chromatography with a Ionpac AS23 4\*250  
277 mm column and the Dionex 7 anions standard solution;

278 cations ( $\text{Li}^+$ ,  $\text{Na}^+$ ,  $\text{NH}_4^+$ ,  $\text{K}^+$ ,  $\text{Mg}^{2+}$ ,  $\text{Ca}^{2+}$ ) using the Thermo Fisher  
279 Scientific Dionex ICS1100 ionic chromatography with a Ionpac  
280 CS12A 4\*250 mm column and the Dionex 6 cations standard  
281 solution. The error margins were of  $\pm 4-6\%$  and  $\pm 2-4\%$   
282 respectively for anions and cations. These analyses are reliable  
283 since all the 839 ionic balances (837 monthly + punctual  
284 samples 3 and 103) are under 10% with even 95.1% under 5%.

285 From July 2014 to March 2017, only groundwater from the  
286 six observation boreholes has been analyzed for stable  
287 isotopes. Since April 2017, all sites have been sampled for  $\delta^2\text{H}$   
288 and  $\delta^{18}\text{O}$  analyses, so the database accounts for 360 isotopic  
289 analyses. Waters have been collected with no air bubbles, in  
290 20 mL borosilicate glass vials closed by polypropylene caps.  
291 Isotopic analysis were performed at the University of Corsica,  
292 France (CNRS UMR 6134 SPE): both  $^2\text{H}$  and  $^{18}\text{O}$  of the water  
293 molecule were characterized using a liquid-water stable  
294 isotope analyzer DLT-100 (Los Gatos Research) according to  
295 the analytical scheme recommended by the IAEA (IAEA, 2009;  
296 Penna et al., 2010). Isotopic data were reported in the  
297 standard delta notation in part per thousand relative to Vienna  
298 Standard Mean Ocean Water (VSMOW; (Clark and Fritz,  
299 1997)). The accuracy is 1‰ for  $\delta^2\text{H}$  and 0.1‰ for  $\delta^{18}\text{O}$ .

300 **3.3. Geophysical investigations**

301 Electrical Resistivity Tomography (ERT) is a geophysical  
302 method providing images of electrical resistivity  $\rho$  (inverse of  
303 conductivity) of the subsurface. ERT is generally used to  
304 characterize the lithology and the geometry of the ground, to  
305 assess its saturation, or even to monitor soil pollution (Loke,  
306 2011). The technique consists of injecting current in a pair of  
307 electrodes set into the ground and measuring the resulting  
308 potential difference between another dipole of electrodes  
309 which yields information about  $\rho$ .

310 A 2D ERT survey was carried out on the SOAHAL  
311 Observatory on the 02/21/2018 in order to investigate  
312 potential underground connections between Auzon Oxbow  
313 and Allier River. The data collection was done by using a  
314 SYSCAL R1+ (Iris instruments), with a Wenner-Schlumberger  
315 electrode configuration (Loke and Barker, 1996). An array of  
316 72 electrodes was installed, distributed every 3 m, along a  
317 NNW-SSE line (Figure 1c). The apparent resistivity data were  
318 inverted with RES2DINV software (Loke, 2016) using least-  
319 squares inversion optimization. Inversion converged to RMS  
320 error of 3% after 5 iterations.

321 **4. Results and discussion**

322 **4.1. End-members characterization and interactions**

323 *4.1.1. Hydrodynamical data*

324

325 Allier River discharge presents an average value of  $25 \text{ m}^3 \cdot \text{s}^{-1}$  for  
326 the studied period (07/22/2014 – 11/24/2017). The most  
327 important flood impulse reached  $328 \text{ m}^3 \cdot \text{s}^{-1}$  (11/23/2016)  
328 while two other flood peaks have been registered equal or  
329 superior to  $150 \text{ m}^3 \cdot \text{s}^{-1}$  ( $156 \text{ m}^3 \cdot \text{s}^{-1}$  on the 11/29/2014 and  $150$   
330  $\text{m}^3 \cdot \text{s}^{-1}$  on the 04/06/16; Figure 2d). These events are quite  
331 moderate compared to the large floods that Allier River can  
332 historically experience (10Y-flood and 50Y-flood: 590 and 840  
333  $\text{m}^3 \cdot \text{s}^{-1}$  respectively; Banque Hydro, n.d.). Annual discharge  
334 variations are observed with globally low flow (LF) periods  
335 during the warmest months (from July to October) with an  
336 average flow rate around  $14 \text{ m}^3 \cdot \text{s}^{-1}$  while high flow (HF)  
337 periods including important flood events occur along the rest  
338 of the year with an average flow rate around  $32 \text{ m}^3 \cdot \text{s}^{-1}$ . This LF-  
339 HF distribution over time is more consistent with variations of  
340 precipitation recorded in the upstream mountainous area  
341 (Mohammed et al., 2014), whose Naussac weather station is  
342 the witness (Figure 2a), than the local ones (represented by  
343 Sainte-Florine weather station on Figure 2a). However, the  
344 maximum flood peak of  $328 \text{ m}^3 \cdot \text{s}^{-1}$  is actually related to high

345 precipitation recorded at both stations, suggesting a  
346 generalized rainfall event linked to a Cevénol episode (a  
347 climatic phenomenon more and more frequent these last few  
348 years with rainy events that mainly affects the Cevennes'  
349 mountain range and piedmont which often cause severe  
350 floods in the Massif Central Region) (Jubertie, 2006; Gay,  
351 2015). On the contrary, flood peak occurring the 01/26/2017  
352 seems to be only due to high altitude precipitation: rainfall  
353 event is actually only recorded at Naussac weather station.  
354 Finally, flood peak recorded the 08/30/2017 is caused by a  
355 stormy event affecting Saint-Florine weather station only.  
356 These examples emphasize that discharge variations recorded  
357 for Allier River are related to a large set of meteorological  
358 conditions affecting the entire Allier basin, including rapid  
359 winter temperature elevation with or without rainfall causing  
360 snow melting (Jubertie, 2006).

361

362 **Figure 2**

363

364 Water level variations at the Auzon Oxbow/Allier River  
365 confluence (solid black lines in Figure 2b and Figure 2c) are  
366 consistent with discharge variations of the Allier River  
367 recorded at Agnat-Pont d'Auzon station (Figure 2d). It shows

368 the accuracy of the *in situ* surface water level monitoring  
369 which was therefore crossed with water table monitoring for  
370 piezometric mapping (triangular interpolation). Figure 3a and  
371 Figure 3b present LF (08/04/2015) and HF (04/06/2016)  
372 piezometric maps, respectively. These two dates are identified  
373 on Figure 2d. The LF piezometric map indicates a global  
374 northward circulation of groundwater (GW) and identified GW  
375 as a potential end-member supplying Auzon Oxbow. Water  
376 level time-series observation (Figure 2b and Figure 2c) shows  
377 that PZ1 and PZ2 (RB) as well as PZ4 (LB) present very  
378 impulsive variations. They were pretty close to the water level  
379 variations at the confluence Auzon Oxbow/Allier River.  
380 Moreover, in HF, piezometric levels were lower than surface  
381 water levels with 0.7% of the records at PZ1, 0.3% at PZ2 and  
382 4% at PZ4. This observation suggests that GW are supplied by  
383 surface water, whatever bank considered, during HF. PZ3, PZ5  
384 and PZ6 (LB) show smoother signals (Figure 2b); most of the LB  
385 piezometric level variations remained consistent with the  
386 surface water level variations.

387

388 **Figure 3**

389

390 The HF piezometric map illustrates the hydrodynamic situation  
391 during the third most important flood event of the studied  
392 period. This flood was linked to a large rainfall event which  
393 affected the whole Allier River catchment (Figure 2a). The map  
394 can be used to identify potential hydrodynamic changes  
395 compared to LF situation. Then an inversion of the hydraulic  
396 gradient is induced by high surface water level recorded at the  
397 Auzon Oxbow/Allier River confluence; it affects GW on both  
398 Auzon Oxbow banks. However, in the RB, inversion is reduced  
399 to a GW flow inversion (from PZ2 to PZ1) since the Allier River  
400 discharge just began to decline while the RB is still in charge.  
401 On the LB, inversion seemed to extend from surface water to  
402 PZ5 passing through PZ4. Actually, during that HF event as  
403 generally for all HF recordings, PZ4 levels varied synchronously  
404 with the surface water level up to inversion of hydraulic  
405 gradient while the other LB boreholes remained stable, PZ5  
406 included. PZ3 piezometric level starts to increase only 24h  
407 after the rise of surface water level, the response delay of PZ5  
408 and PZ6 is about 26h. Besides, PZ5 piezometric level stays  
409 lower than the one of PZ6, inducing a piezometric depression.  
410 The delay between the increase in surface water level and that  
411 of the more inland LB boreholes suggests that the hydraulic  
412 gradient inversion is limited to PZ4. This hydrodynamic feature  
413 can be explained by high disparities existing within the alluvial

414 deposits (from silts to gravels; Teles et al., 2004; Ounaïes et al.,  
415 2013; Sarris et al., 2018). These 3D heterogeneities lead to  
416 variations in water flows distribution within the aquifer.

417 To summarize, hydrodynamic data highlight that during LF,  
418 Auzon Oxbow is supplied by GW. During HF, an inversion of  
419 the hydraulic gradient is recorded and Auzon Oxbow  
420 contributes to the recharge of GW. RB is entirely concerned by  
421 this recharge while only the oxbow closest borehole (PZ4) is  
422 affected in the LB (Figure 3b). The important time delay  
423 observed between surface water flood peaks and GW  
424 recharge at PZ3, PZ5 and PZ6 (from 24 to 26h) indicates that  
425 LB GW is mainly recharged by the southern GW system.

426

#### 427 *4.1.2. Physico-chemical data*

428

429 For the 21 sample sites, physico-chemical parameters  
430 measurements (water temperature – T; pH; electrical  
431 conductivity – EC) as well as ions concentrations and water  
432 stable isotopes determinations are presented in Table 1 with  
433 average (arithmetic means), minimum, maximum and  
434 standard deviation values. EC vs T data of the entire SOAHAL  
435 observatory are reported in Figure 4a while EC time-series of  
436 Auzon Oxbow DZ (B2bis), IZ (B4), UZ (B7) and of each end-

437 member are quoted in Figure 4b: Allier River, PZ1 (RB GW),  
438 PZ3-PZ4 (LB GW with an increasing distance to the Auzon  
439 Oxbow from PZ4 to PZ3).

440 The pH values are comprised between 6.5 and 8.8 (Table  
441 1), which is consistent with natural water pH usually ranging  
442 from 6.5 to 9.5. The more neutral values have been recorded  
443 in GW and are assumed to be due to the buffering capacity of  
444 soils. EC and T values were the most interesting physico-  
445 chemical parameters to differentiate water end-members  
446 (Figure 4):

- 447 - Allier River EC is the lowest one within the study site  
448 ( $110 \pm 17 \mu\text{S}\cdot\text{cm}^{-1}$ ; Table 1), without any significant  
449 variations during the year (Figure 4b). On the contrary  
450 T experiences high amplitudes (from 0.9 to 21.8°C;  
451 Table 1) as an impact of air temperature annual  
452 variation.
- 453 - PZ1 and PZ2 show the lowest EC values of the  
454 boreholes (with 290 and 491  $\mu\text{S}\cdot\text{cm}^{-1}$  respectively;  
455 Table 1). EC annual variations are relatively low (Figure  
456 4b) while T amplitudes can reach more than 12°C  
457 (Table 1). The RB (P2, P4, P6, and P9) and LB (P7) near-  
458 surface piezometers (Figure 1c) also present low EC  
459 values and high T amplitudes (Figure 4a and Table 1).

460 - PZ3 to PZ6 are characterized by the highest EC values  
461 (mean value of the four boreholes:  $981 \mu\text{S}\cdot\text{cm}^{-1}$ ) while T  
462 experienced the smaller variations (around  $7^\circ\text{C}$ ; Table  
463 1). EC time-series show a quite stable signal with no  
464 clearly identified seasonal variations (Figure 4b). P3  
465 and P5, the two remaining LB near-surface piezometers  
466 (Figure 1c) present similar EC and T patterns (Figure 4a  
467 and Table 1).

468 - Le Monteil spring shows a high EC value ( $925 \mu\text{S}\cdot\text{cm}^{-1}$ ,  
469 Table 1) and low amplitude of T ( $6.7^\circ\text{C}$ ; Table 1) which  
470 is consistent with the LB GW (Figure 4a).

471

472 **Table 1**

473

474 **Figure 4**

475

476 *4.1.3. Hydrochemical data*

477

478 Hydrochemical data of Table 1 have been plotted on a  
479 Piper diagram (Figure 5) in order to define the geochemical  
480 water-types of each end-member. Water types are distributed  
481 between two groups with a noticeable difference in the  
482 cations content. The first group has a Ca-Na/ $\text{HCO}_3$  type and

483 includes Allier River, PZ1-PZ2 (RB GW), P2-P4-P6-P9 (RB near-  
484 surface piezometers), P7 (LB near-surface piezometer) and  
485 then the second group presents a Ca/HCO<sub>3</sub> signature and  
486 corresponds to PZ3 to PZ6 (LB GW), P3 and P5 (the two  
487 remaining LB near-surface piezometers) and Le Monteil Spring.  
488 Then, the GW signal shows a clear distribution between RB  
489 and LB. RB GW are predominantly supplied by Allier River  
490 whereas LB GW chemical facies is consistent with the one of  
491 the plateau aquifer (Le Monteil). This is in agreement with  
492 hydrodynamic data. P7 can be quoted as an exception to this  
493 RB/LB GW distribution, as this LB near-surface piezometer  
494 presents physico-chemical and geochemical characteristics  
495 close to the RB GW ones.

496 Chemical difference between Allier River (as well as RB  
497 GW) and LB GW is due to the geological composition of the  
498 watershed. Actually, the Ca-Na/HCO<sub>3</sub> water type of the Allier  
499 River can be related to the volcano-metamorphic basement:  
500 upstream of the study site, the Allier River incised the  
501 basement while downwards, the riverbed widens within the  
502 Brioude basin where an enrichment in calcareous nodules  
503 between Vieille Brioude and the study site has been  
504 documented (Lasnier and Marchand, 1982). Carbonate  
505 dissolution occurrences are reported in the Allier River and the

506 shallow GW associated (Négre<sup>l</sup> et al., 2004). Sodium minerals,  
507 subjects to weathering, are reported as common in the Allier  
508 terraces, as augite, green and brown hornblende and  
509 nepheline (Rudel, 1963; Pastre, 1986; Veldkamp and  
510 Jongmans, 1990), which explain the Na-enriched signature of  
511 the Allier River and so that of the RB GW. The Ca/HCO<sub>3</sub> water  
512 type of LB GW has been already described by several authors  
513 (Négre<sup>l</sup> et al., 2004; Vanderhaeghe and Prognon, 2012;  
514 Mohammed et al., 2014) and corresponds to many alluvial  
515 aquifers in France (Roux, 2006) and over the world (Chkirbene  
516 et al., 2009; Andrade and Stigter, 2011; Huang et al., 2014).  
517 Indeed, because the mineral phases that composed alluvial  
518 aquifers do not generally impose a very marked geochemical  
519 type and because of short residence times within the aquifer,  
520 alluvial GW presents frequently a Ca/HCO<sub>3</sub> water type (Roux,  
521 2006).

522

523 **Figure 5**

524

525

526 **4.2. Auzon Oxbow as a result of the mixing between end-**  
527 **members**

528 *4.2.1. General features of Auzon Oxbow chemistry*

529

530 In a first approximation, taking into account their origin,  
531 perfluvial oxbows and main stream are supposed to have a  
532 similar chemical composition (Négre et al., 2003). However,  
533 despite its still active connection with the Allier River, the  
534 Auzon Oxbow presents a mean EC value ( $300 \mu\text{S}\cdot\text{cm}^{-1}$ ) higher  
535 than Allier River one ( $110 \mu\text{S}\cdot\text{cm}^{-1}$ ) but lower than GW ( $784$   
536  $\mu\text{S}\cdot\text{cm}^{-1}$  in mean for observation boreholes of both banks). This  
537 indicates that the Auzon Oxbow water results from a mixing  
538 between the low concentration water of the Allier River and  
539 the more concentrated one of GW, whatever the bank (Table  
540 1, Figure 4). Figure 6 confirms this trend and highlights a clear  
541 evolution of the Auzon Oxbow between a Na-pole  
542 characterized by Allier River and a more calcic end member  
543 delineated by LB GW. RB GW water type is close to the Auzon  
544 Oxbow one and seems to result also from the mixing between  
545 Allier River and LB GW. The proximity of LB GW and Le Monteil  
546 spring confirms the contribution of the plateau aquifer to the  
547 alluvial GW. This general feature is however not constant  
548 within the hydrological cycle: records of April 2016

549 (highlighted by the grey area of Figure 4b) show a decrease of  
550 Auzon Oxbow EC which reaches the value of Allier River. This  
551 specific period corresponds to one of the major floods that  
552 have affected the Allier River during the study, with a  
553 discharge flow of  $150 \text{ m}^3 \cdot \text{s}^{-1}$  registered on the 04/06/16 (Figure  
554 2d). During this period, the Allier River penetrated further into  
555 the Auzon Oxbow. This surface water arrival, characterized by  
556 a low concentration, affected the Auzon Oxbow up to B6, B7  
557 showing constant EC. This was a short-time process since  
558 Auzon Oxbow recovered its pre-flood concentration the  
559 month after (Figure 4b), indicating that the oxbow restitutes  
560 quickly to the main stream what it absorbs during flood. This  
561 time-constrain phenomenon has already been quoted for  
562 oxbows by Carrel and Juget, (1987) for the Morte du Sauget,  
563 one of the Rhône oxbows and for oxbows of Ain River (Le Coz,  
564 2003). PZ4 records also an EC decrease in April 2016, in  
565 accordance with the inversion of the hydraulic gradient  
566 showed in HF piezometric map (Figure 3b).

567

568 **Figure 6**

569

570

571

572 4.2.2. Identification of punctual arrivals of GW within Auzon

573 *Oxbow*

574

575 To precise the downstream-upstream evolution within the  
576 Auzon Oxbow, a fine cartography of EC has been performed on  
577 the 11/23/2017, during a low flow stage (Allier River daily  
578 discharge:  $6.7 \text{ m}^3.\text{s}^{-1}$ ). Figure 7 presents the results of this  
579 campaign and puts in evidence a difference between the  
580 upstream zone characterized by low EC values, mainly in the  
581 range  $0\text{-}250 \text{ }\mu\text{S}.\text{cm}^{-1}$ , and IZ and DZ parts of the Auzon Oxbow  
582 with values comprised between 250 and  $400 \text{ }\mu\text{S}.\text{cm}^{-1}$ . This  
583 general pattern is disturbed by local arrivals of water. A high  
584 EC is observed along the downstream zone left bank (point  
585 103 =  $735 \text{ }\mu\text{S}.\text{cm}^{-1}$ ; Figure 7) and testifies for a high  
586 concentration groundwater arrival. On the contrary, the whole  
587 upstream part is characterized by low EC in accordance with  
588 low concentration water incomes, some of which were  
589 identified as coming from the bed of the oxbow. Points 3 (as  
590 an example of the latter) and 103 have been sampled for ions  
591 analyses.

592

593 **Figure 7**

594

595 Physico-chemical parameters and ions concentrations of  
596 samples acquired on the 11/23-24/2017 for the points 3, 103  
597 and the 21 followed sites are reported in Table 2. Results show  
598 that:

599 - Point 103 presents a Ca/HCO<sub>3</sub> signature pretty close to  
600 that of LB GW (Figure 8) and especially PZ4 (Table 2,  
601 Figure 8). PZ4 shows higher NO<sub>3</sub><sup>-</sup> (13.1 mg.L<sup>-1</sup>) probably  
602 due to a contamination of alluvial GW, but not  
603 transmitted or degraded before the transfer LB GW to  
604 Auzon Oxbow.

605 - The low concentration water arrival located at the UZ  
606 end of the oxbow (Point 3) presents a Ca-Na/HCO<sub>3</sub>  
607 water type similar to Allier River one (Table 2, Figure  
608 8). This is in accordance with an upstream supply by  
609 the Allier River. The water arrival of Point 3 was coming  
610 from the bed of the oxbow which indicates that this  
611 supply is realized through underground inflows. The  
612 location of these low concentration water arrivals  
613 directly close to the paleochannel visible in the  
614 landscape, suggests that an old and deeper channel  
615 connects Auzon Oxbow to Allier River. The potential  
616 recharge by underground paleochannels, because of  
617 their high hydraulic conductivity, has already been  
618 observed (Rathore et al., 2010; Babka et al., 2011).

619

620 **Table 2**

621

622 **Figure 8**

623

624 Therefore, to verify the present hypothesis, an ERT  
625 sounding has been performed on the 02/21/2018 (high flow  
626 period, Allier River daily discharge =  $57.3 \text{ m}^3 \cdot \text{s}^{-1}$ , see part 3.3).  
627 The location of the profile is indicated in Figure 1c. Oriented  
628 SSE-NNW, the profile was designed perpendicularly to the  
629 visible paleochannel and close to the upstream end of the  
630 Auzon Oxbow. Indeed, electrical resistivity sounding has  
631 already been used to investigate subsurface paleochannel  
632 geometry, architecture and hydrodynamic (Sinha et al. 2013)  
633 as well as fresh GW discharge through a paleochannel (Kolker  
634 et al., 2013). The resulting ERT profile indicates a general  
635 decrease of the electrical resistivity with depth (Figure 9). Two  
636 main zones can however be observed. In the first one, from  
637 surface to 8-10 m depth, resistivity varies laterally. The  
638 southern part of the profile, along with the 48 first lateral  
639 meters on Figure 9, presents a relatively low resistivity ( $\rho =$   
640  $150 \text{ to } 350 \text{ } \Omega \cdot \text{m}^{-1}$ ) compared to the rest of the section ( $\rho > 600$   
641  $\Omega \cdot \text{m}^{-1}$ ). It can be interpreted as a sand formation saturated

642 with freshwater (Sinha et al., 2013). This is consistent with the  
643 presence of the paleochannel of the Allier River (Figure 1c),  
644 which higher porosity induces lower resistivity (Archie, 1942).  
645 In addition, there is lateral resistivity change within the  
646 paleochannel which most likely reflects the progressive filling  
647 of the system and a potential connection to the river (blue  
648 circle on Figure 9). The second zone starts below 10 m depth  
649 with low resistivity values and corresponds to the Oligocene  
650 marl substratum (Lasnier and Marchand, 1982; Korobova et  
651 al., 1997).

652

653 **Figure 9**

654

655 This paleochannel supplies the Auzon Oxbow with low  
656 concentration water and explains the low EC and the water  
657 types observed in the upstream part of the Auzon Oxbow and  
658 in the near-surface piezometer P7 (Figure 1c). The repartition  
659 of Auzon Oxbow points along the mixing line of the Figure 6,  
660 with B7 closer to the Allier River end-member than B2 is thus  
661 explained. For information, a simple estimation of contribution  
662 percentages of Allier River and LB GW to the oxbow (at its  
663 different sampling locations) can therefore be deduced  
664 from the Figure 6 data. Indeed, considering that the chemical

665 characteristics of the Allier River end-member point (30.2 mg.l<sup>-1</sup>  
666 <sup>1</sup> of HCO<sub>3</sub><sup>-</sup> and a Na/Ca ratio of 0.95) represent 100% of  
667 contribution from the main stream and that those of LB GW  
668 (302.6 mg.l<sup>-1</sup> of HCO<sub>3</sub><sup>-</sup> and a Na/Ca ratio of 0.23) represent 0%,  
669 it is easy to deduce the contributions of those end-member to  
670 the oxbow at the different sampling sites. So, it was logically  
671 estimated that B2, the closest location to the confluence and  
672 B7, the closest location to the paleochannel arrival, were  
673 mostly and equally fed by the Allier River with respectively 63  
674 and 64 % of contribution. The rest of the oxbow would be,  
675 according to these strictly indicative estimates, as much fed by  
676 the river as by the alluvial groundwater (49 % of Allier River  
677 contribution for B3, 50 % for B4 and 51 % for B2bis and B6).  
678 Those estimates would imply that alluvial groundwater  
679 contributions to the Auzon oxbow are not negligible and that,  
680 in terms of contribution share, the river contributes as much  
681 by the confluence as by the upstream paleochannel to the  
682 oxbow water supply.

683

684 *4.2.3. Use of  $\delta^2H$  and  $\delta^{18}O$  of the water molecule for temporal*  
685 *insight*

686

687 The  $^2\text{H}$ - $^{18}\text{O}$  stable isotopes of the water molecule  
688 constitute one of the best water tracers since it provides  
689 information about water origins as well as water mixing  
690 processes through the hydrological cycle (Fontes, 1980; Clark  
691 and Fritz, 1997; Kendall and McDonnell, 1999). For the study  
692 of wetlands, they allow approaching their functioning (Hunt et  
693 al., 1998; Clay et al., 2004) and more peculiarly to characterize  
694 the isotopic content of the different supplying sources or the  
695 Auzon Oxbow (Babka et al., 2011) according to the  
696 temperature-, amount-, altitudinal- and continental-effects  
697 (Rozanski et al., 2001).

698 For coherent interpretations, data from April to November  
699 2017, period of the concomitant investigation of all sites, have  
700 been selected among the database. Allier River ( $-8.0 \delta^{18}\text{O}\text{‰}$ , -  
701  $52.0 \delta^2\text{H}\text{‰}$ ) and RB GW ( $-8.1 \delta^{18}\text{O}\text{‰}$ ,  $-53.2 \delta^2\text{H}\text{‰}$ ) present the  
702 most depleted isotopic content. The LB GW ( $-7.7 \delta^{18}\text{O}\text{‰}$ ,  $-51.5$   
703  $\delta^2\text{H}\text{‰}$ ) and Le Monteil spring ( $-7.3 \delta^{18}\text{O}\text{‰}$ ,  $-50.0 \delta^2\text{H}\text{‰}$ ) are  
704 characterized by more enriched signatures. As previously  
705 referred by Négrel et al. (2003) and by Mohammed et al.  
706 (2014), Allier River displays a clear seasonal variation (Figure  
707 10a) with depleted values during winter and more generally  
708 during HF period (around  $-8.5 \delta^{18}\text{O}\text{‰}$ ) than for summer  
709 (around  $-7.5\text{‰}$ ), mainly due to the temperature effect on

710 precipitation. Figure 10b shows  $\delta^2\text{H}_{\text{VSMOW}}$  (‰) vs  $\delta^{18}\text{O}_{\text{VSMOW}}$   
711 (‰) means for Auzon Oxbow sampling sites and its end-  
712 members. Taking into account the high variability of the Allier  
713 River data, all the measurements have been plotted  
714 individually. Precipitation is represented by the Global  
715 Meteoric Water Line (GMWL) of Craig (1961), and more  
716 regionally by the Local Meteoric Water Line (LMWL) proposed  
717 by Petelet-Giraud et al. (2005) with a local average of  $\delta^2\text{H} = 8*$   
718  $\delta^{18}\text{O} + 13.7\text{‰}$  and low altitude rainfalls of Cournon  
719 ( $03^{\circ}13'33''\text{E}/45^{\circ}44'54''\text{N}$ ; elevation: 327 m; period 2013-2016;  
720 AUVERWATCH Database, 2018; Celle-Jeanton, 2017). All data  
721 follow a trend line between LMWL and local precipitation of  
722 Cournon rainfall, the more depleted signal is characterized by  
723 the samples of Allier River during HF ( $-8.5 \delta^{18}\text{O}\text{‰}$ ,  $-55.0 \delta^2\text{H}\text{‰}$ )  
724 while the more enriched by the Allier River LF ones ( $-7.4$   
725  $\delta^{18}\text{O}\text{‰}$ ,  $-49.1 \delta^2\text{H}\text{‰}$ ), LB GW ( $-7.7 \delta^{18}\text{O}\text{‰}$ ,  $-51.5 \delta^2\text{H}\text{‰}$ ) and Le  
726 Monteil spring ( $-7.3 \delta^{18}\text{O}\text{‰}$ ,  $-50.0 \delta^2\text{H}\text{‰}$ ). Allier River HF data  
727 follow the LMWL and are representative of the colder and  
728 higher altitude precipitation. The more enriched and  
729 evaporated signal of Allier River LF is explained by low altitude  
730 precipitation (summer local storms) and/or local GW supply.  
731 This is consistent with the previous conclusions based on  
732 hydrodynamic data that showed relationships between low  
733 flow surface water and groundwater, with more enriched GW

734 during summer, due to evaporation process (Geyh and Mook,  
735 2000; Mohammed et al., 2014). Auzon Oxbow isotopic data  
736 are well plotted along a mixing line between Allier River HF  
737 and isotopically enriched waters. Auzon Oxbow DZ (B2 and  
738 B2bis) presents the more enriched and evaporated signal close  
739 to that of the LB GW; the heavy isotopes content globally  
740 decreases up to the UZ (B7; Figure 10b). On a temporal scale,  
741 evolution of isotopic data in the Auzon Oxbow tends to  
742 homogenize and the 3 identified zones DZ (B2bis), IZ (B4) and  
743 UZ (B7) present, in winter period, the same isotopic content  
744 (Figure 10a). This behavior is partly explained by previous  
745 observations: DZ is subject to a double supply through its  
746 connection to the Allier River at the confluence and LB GW  
747 inputs (Point 103). The later explains the more enrich isotopes  
748 contents and its important variations through time. B7 has  
749 been shown to be supplied by Allier River that inflows to the  
750 Auzon Oxbow through the subsurface paleochannel. However,  
751 B7 presents a behavior completely different from the one of  
752 Allier River and isotopic values of B7 match only the Allier  
753 River ones during winter high flow period (Figure 10a). This  
754 observation provides precision about the recharge of the  
755 Auzon Oxbow from the paleochannel that occurs only  
756 seasonally, during HF periods, as for the RB GW. Indeed,  
757 according to the hydrodynamic monitoring, the RB GW

758 recharge through inversion of the hydraulic gradient during HF  
759 which is also in agreement with the depleted isotopic values  
760 observed for RB GW.

761

762 **Figure 10**

763

#### 764 **4.3. Conceptual model of the Auzon Oxbow**

765 The multidisciplinary analysis between hydrodynamic,  
766 geochemical and isotopic approaches carried out at the dense  
767 SOAHAL Observatory allows establishing a reliable conceptual  
768 model of the hydrodynamical functioning of the Auzon Oxbow  
769 (Figure 11). As expected for that kind of perfluvial  
770 environments (Rollet et al., 2005), interactions between the  
771 oxbow and both the main stream and the alluvial aquifer were  
772 identified. Since the Auzon Oxbow is disconnected from the  
773 main stream in its upstream end for the last 30 years, the  
774 Allier River supplies the oxbow generally through the  
775 downstream confluence (surface water flows on Figure 11).  
776 However, during major flood events the main stream can  
777 submerge the right bank and then supply the entire oxbow  
778 area. Geochemical data show another interaction between the  
779 Allier River and the Auzon Oxbow, through the upstream  
780 underground paleochannel, recognized both via geochemical

781 analysis and geophysical investigations. A detailed isotopic  
782 analysis has shown that this Auzon Oxbow area has a similar  
783 isotopic signature than Allier River during high flow periods  
784 only. This observation implies that the paleochannel is active  
785 from November to June only. This is in agreement with the  
786 results of hydrodynamic and geochemical approaches which  
787 identified existing pathways from surface water to alluvial  
788 groundwater during the same periods (high flow GW flows on  
789 Figure 11).

790

791 **Figure 11**

792

793 The coupling approach also testifies for a supply of the  
794 oxbow by the alluvial groundwater, this especially affects the  
795 water composition in its downstream part. As this part of the  
796 oxbow is the site of its confluence to the Allier River,  
797 groundwater supply could have been underestimated  
798 otherwise. That connection with the adjunct alluvial aquifer is  
799 active during low flow (Figure 11). LB GW are mainly supplied  
800 by the southern part of alluvial aquifer and the neighboring  
801 agricultural plateau (permanent GW flows on Figure 11),  
802 except during high floods when small gradient inversions can  
803 drive pathways from surface water to groundwater.

804 The active connection existing between the Auzon Oxbow  
805 and the Allier River through the underground paleochannel  
806 would not have been identified and specified without the  
807 geochemical and isotopic approaches. A standard  
808 hydrodynamic study based on their apparent  
809 geomorphological surface connection would have produced an  
810 incomplete understanding of the Auzon Oxbow hydrosystem.  
811 Besides, while studies attest for the importance of oxbow  
812 connection degree to the main stream on the water quality  
813 (Carrel and Juget, 1987; Bengen et al., 1992), it is mostly based  
814 on the type of surface connection observed between the two  
815 water bodies (oxbow isolated from the river or connected  
816 through one or two sides as Ward et al. (2002) described).  
817 Those observations indeed inform about the extent of the  
818 hydrological connection that impacts the water chemistry of  
819 oxbows (Tockner et al., 1999; Glińska-Lewczuk, K., 2009)  
820 especially for instance for metals contaminations (Ciazela et  
821 al., 2018). However, the present study show that consequent  
822 underground connection can also occur between the main  
823 stream and the oxbow through paleochannel as already  
824 suggested by Babka et al. (2011), increasing so their apparent  
825 connection degree and impacting the water chemistry of the  
826 oxbow. Therefore, the possibility of underground connectivity  
827 to the main stream should be further considered in oxbows

828 hydrogeological studies. Applying multidisciplinary approach  
829 as the one performed on the Auzon Oxbow should so be  
830 essential to the establishment of reliable conceptual models  
831 and to their resulting management applications.

832

833 **5. Conclusions**

834 In a near future, wetlands like oxbows are assumed to become  
835 more and more determinant as nature-based solutions to  
836 respond to hydrological (river discharge control) and ecological  
837 (excess nutrients removal function) concerns. Therefore, the  
838 dynamic of these specific hydrosystems must be fully  
839 understood. However, the establishment of complete and  
840 usefull functioning models is complicated by the different  
841 connection degrees that can have these specific wetlands with  
842 the surrounding water masses. The task is all the more difficult  
843 since it is usually undertaken through individual investigation  
844 approach which can neglect or underestimate some supply  
845 components. The objectives of the present study were so to  
846 provide effective diagnostic tools to evaluate oxbow  
847 connection degree to the main stream and to the adjunct  
848 alluvial aquifer in order to be able to establish a complete  
849 hydrodynamic description of such hydrosystems.

850 The Auzon Oxbow conservation is the subject of local/regional  
851 great concerns especially for the local fishing associations. In  
852 fact, hydrodynamic and hydrochemical features of Auzon  
853 Oxbow have a direct impact on its ecological functions as  
854 reproduction and refuge areas for emblematic fishes such as  
855 trouts. This study so proposed the coupling of hydrodynamic,

856 geochemical and isotopic approaches to produce a model  
857 which can serve as a reference state for further operations of  
858 conservation and management of the Auzon Oxbow. The  
859 conceptual model thus produced attests to a greater degree of  
860 connection than expected between the Auzon Oxbow and  
861 both the main stream and the alluvial aquifer. Indeed, despite  
862 their surface upstream disconnection for the last 30 years, the  
863 study proved that Allier River supplies the oxbow through the  
864 downstream confluence and through the upstream  
865 underground paleochannel. Besides, the model attests to a  
866 non-negligible supply of the Auzon oxbow by the adjunct  
867 alluvial aquifer.

868 The current model can however be improved by  
869 completing the present hydrodynamic monitoring set with  
870 hydrological stations within the oxbow: one at the upstream  
871 ends of its downstream zone to compare data with the current  
872 hydrological station of the confluence; and one at the  
873 upstream end of the oxbow, close to the paleochannel water  
874 arrival. Flowrates measurements must indeed be performed in  
875 order to be able to quantify the water fluxes identified in this  
876 paper. Thus, the Auzon Oxbow role to manage flood events in  
877 the Allier River system would be evaluated. Besides, the  
878 impact of the Allier River arrival through the paleochannel on  
879 the water level of the upstream zone of the oxbow would be

880 assessed. Furthermore, such reliable conceptual models can  
881 be used for further applications: strategic wetlands operations  
882 or water quality managements responding to environmental  
883 and/or ecological issues. Indeed, such hydrodynamic  
884 knowledges on hydrosystems constitute an essential  
885 requirement to understand the transport of polluting  
886 substances by water. The conceptual hydrodynamic scheme  
887 coupled with the contaminants observations can support the  
888 assessment of the origin(s) and fate(s) of pollutants within  
889 wetlands hydrosystems and the identification of potential  
890 remediation processes occurrences. The present conceptual  
891 model of the Auzon Oxbow hydrosystem is currently used to  
892 assess the role of that wetland regarding to excess nutrients  
893 and emerging molecules dynamics.

894 The study here proved that coupling several investigation  
895 approaches such as hydrodynamic (surface water and  
896 groundwater levels), geochemical (physico-chemical  
897 parameters and ionic concentrations) and isotopic ( $\delta^2\text{H}$ - $\delta^{18}\text{O}$   
898 of the water molecule) monitorings actually efficiently  
899 supports the identification of water supply sources to the  
900 wetland through space and time. Indeed, while the  
901 hydrodynamic approach gives general informations about  
902 surface water/grounwater interactions, the geochemical and

903 isotopic approaches complete the overview by identifying the  
904 origin of water, imaging the hydrochemistry of the oxbow and  
905 following the evolution of hydrodynamical and chemical  
906 parameters within time. Spatial and temporal disparities in the  
907 oxbow connection degree to the main stream and to the  
908 alluvial groundwater are proved to largely depend on river  
909 discharge during low and high flows. Besides, relevance of  
910 considering the degree of underground connection between  
911 the oxbow and the river was highlighted. The used of the  
912 multidisciplinary approach proposed here to image oxbows is  
913 then very promising.  
914

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920 Besides, the study was carried out in an interdisciplinary  
921 setting under the aegis of the FR Environnement. Thanks also  
922 to the farmers of the study area who authorized the  
923 observation boreholes installation on their fields.

Sample ID	T (°C)	pH	EC ( $\mu\text{S.cm}^{-1}$ )	HCO <sub>3</sub> <sup>-</sup>	Cl <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	NO <sub>3</sub> <sup>-</sup>	NO <sub>2</sub> <sup>-</sup>	PO <sub>4</sub> <sup>3-</sup>	F <sup>-</sup> ( $\text{mg.l}^{-1}$ )	Na <sup>+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>	K <sup>+</sup>	NH <sub>4</sub> <sup>+</sup>	Li <sup>+</sup>	$\delta^2\text{H}$ (‰ VSMOW)	$\delta^{18}\text{O}$ (‰ VSMOW)
Allier	Av.	12.3	7.6	110	30.2	9.9	6.1	3.2	0.0	0.1	7.1	7.7	3.2	1.6	0.1	0.0	-52.0	-8.0
	Min.	0.9	7.0	62	12.5	5.4	3.8	1.2	0.0	0.0	3.9	4.4	1.7	1.0	0.0	0.0	-56.7	-8.8
	Max.	21.8	8.8	152	49.0	14.7	10.3	6.7	0.0	0.1	9.6	11.8	4.9	2.6	0.2	0.0	-47.5	-7.1
	SD	6.0	0.4	17	7.8	2.0	1.3	1.4	0.0	0.0	1.2	1.5	0.7	0.3	0.0	0.0	3.4	0.6
B2	Av.	12.6	7.4	242	77.2	19.8	12.1	2.1	0.0	0.1	11.1	21.1	7.4	2.6	0.1	0.0	-51.4	-7.8
	Min.	1.1	6.9	76	16.7	6.6	5.0	0.2	0.0	0.1	4.7	5.1	2.0	1.5	0.0	0.0	-55.7	-8.6
	Max.	22.8	8.0	483	180.0	38.0	25.6	6.7	0.1	0.1	17.9	47.3	19.3	4.5	0.4	0.0	-47.4	-7.2
	SD	5.7	0.2	123	46.9	8.5	5.9	1.5	0.0	0.0	3.9	12.4	4.5	0.8	0.1	0.0	3.0	0.5
B2bis	Av.	12.3	7.2	362	116.1	31.6	17.2	1.9	0.0	0.1	16.0	34.0	10.2	4.0	0.1	0.0	-51.9	-7.9
	Min.	4.7	6.7	116	29.3	9.7	6.5	0.2	0.0	0.1	6.3	8.8	3.0	2.1	0.0	0.0	-52.9	-8.0
	Max.	18.4	7.9	452	151.0	48.7	31.4	8.0	0.1	0.1	20.5	48.3	15.9	20.7	0.2	0.0	-48.0	-7.5
	SD	3.9	0.2	63	24.1	8.2	5.1	1.8	0.0	0.0	2.9	7.8	2.3	2.9	0.1	0.0	1.6	0.2
B3	Av.	12.3	7.2	337	111.9	31.2	15.4	1.7	0.0	0.1	16.5	32.0	9.3	4.0	0.1	0.0	-52.6	-8.0
	Min.	5.5	6.8	140	42.0	12.6	7.4	0.2	0.0	0.1	7.8	11.1	3.5	2.7	0.0	0.0	-53.4	-8.1
	Max.	21.3	7.7	462	155.0	51.6	30.9	7.6	0.2	0.1	20.6	50.1	14.8	24.0	0.3	0.0	-52.0	-7.9
	SD	3.9	0.2	65	19.7	8.4	5.4	1.9	0.0	0.0	2.6	6.7	2.0	3.3	0.1	0.0	0.5	0.1
B4	Av.	12.3	7.1	337	111.1	30.4	14.9	1.9	0.0	0.1	16.5	31.8	9.1	3.5	0.1	0.0	-52.4	-7.9
	Min.	6.0	6.8	155	43.0	13.7	8.2	0.3	0.0	0.1	8.4	12.4	3.9	2.6	0.0	0.0	-53.2	-8.1
	Max.	20.9	7.9	425	133.0	44.6	25.9	7.6	0.1	0.2	20.8	40.5	11.7	4.1	0.3	0.0	-51.0	-7.7
	SD	3.3	0.2	57	17.1	7.4	4.3	1.8	0.0	0.0	2.6	6.0	1.6	0.3	0.1	0.0	0.8	0.2
B6	Av.	13.3	7.1	302	98.3	27.0	12.2	1.5	0.0	0.1	15.5	27.1	7.6	3.4	0.1	0.0	-52.5	-7.9
	Min.	6.6	6.7	210	53.0	17.0	7.3	0.1	0.0	0.1	11.4	16.4	5.3	2.7	0.0	0.0	-53.7	-8.2
	Max.	21.0	8.3	431	135.0	51.2	22.0	6.7	0.0	0.2	22.0	40.1	13.3	4.6	0.2	0.0	-50.8	-7.4
	SD	3.3	0.3	49	16.0	7.3	3.9	1.5	0.0	0.0	2.6	5.3	1.6	0.4	0.1	0.0	0.9	0.2
B7	Av.	12.8	7.0	215	69.7	19.3	8.4	2.3	0.0	0.1	12.2	18.7	5.1	2.7	0.1	0.0	-53.1	-8.1
	Min.	8.6	6.6	157	50.0	10.2	5.7	0.8	0.0	0.1	9.3	13.8	3.8	2.1	0.0	0.0	-54.8	-8.2
	Max.	18.3	7.6	373	95.0	28.8	13.5	9.0	0.0	0.5	16.5	25.8	6.8	5.0	0.2	0.0	-50.4	-7.7
	SD	2.0	0.2	37	10.0	5.1	2.0	1.5	0.0	0.1	1.9	2.6	0.7	0.5	0.1	0.0	1.3	0.2
Monteil	Av.	13.1	7.2	925	235.5	66.1	69.8	97.9	0.0	0.5	14.0	125.3	18.4	15.6	0.1	0.0	-50.0	-7.3
	Min.	9.5	7.0	871	134.0	55.1	60.8	87.0	0.0	0.3	12.3	74.1	16.8	10.6	0.0	0.0	-50.6	-7.5
	Max.	16.2	7.5	1031	273.0	97.3	87.3	120.6	0.1	0.6	18.4	145.6	25.1	47.0	0.3	0.0	-49.4	-7.2
	SD	1.7	0.1	39	26.9	9.3	4.7	7.5	0.0	0.6	1.2	13.5	1.5	7.7	0.1	0.0	0.4	0.1
P2	Av.	12.8	6.9	230	77.6	15.2	12.0	3.2	0.0	0.2	13.3	13.8	9.3	3.0	0.0	0.0	-54.8	-8.4
	Min.	4.9	6.5	147	34.0	8.5	3.1	0.0	0.0	0.1	7.7	7.5	5.4	1.4	0.0	0.0	-55.9	-8.6
	Max.	20.1	7.9	357	131.0	38.7	28.3	10.5	0.0	0.1	19.0	25.3	17.9	14.6	0.2	0.0	-54.0	-8.2
	SD	3.7	0.3	59	24.1	7.2	6.2	3.0	0.0	0.0	3.0	4.7	2.9	3.2	0.0	0.0	0.6	0.2
P3	Av.	12.5	7.1	744	238.5	53.1	61.0	26.0	0.0	0.1	17.3	80.8	28.2	4.2	0.0	0.0	-50.6	-7.6
	Min.	7.6	6.9	215	66.0	13.8	13.7	11.1	0.0	0.1	8.7	19.9	6.8	1.8	0.0	0.0	-51.2	-7.7
	Max.	17.3	7.4	950	293.0	101.0	105.0	46.1	0.1	0.7	23.5	102.1	39.8	7.0	0.2	0.0	-49.9	-7.5
	SD	2.5	0.2	101	34.1	12.9	12.1	6.8	0.0	0.1	2.1	13.9	4.4	0.7	0.0	0.0	0.4	0.1
P4	Av.	12.8	7.0	381	139.4	32.7	7.3	0.2	0.0	0.2	17.0	34.9	10.6	3.5	0.9	0.0	-52.1	-7.9
	Min.	5.1	6.7	287	101.0	21.7	0.1	0.0	0.0	0.1	13.0	26.1	7.5	2.5	0.1	0.0	-52.5	-8.0
	Max.	19.2	7.7	587	203.0	45.5	42.2	0.9	0.0	0.1	22.8	62.0	18.9	4.7	1.9	0.0	-51.4	-7.8
	SD	3.7	0.2	71	22.6	7.7	10.5	0.2	0.0	0.0	2.5	7.9	2.7	0.5	0.4	0.0	0.4	0.1
P5	Av.	12.6	7.1	795	255.4	59.8	65.3	20.4	0.0	0.2	20.0	87.9	29.1	3.1	0.0	0.0	-50.8	-7.6
	Min.	9.2	7.0	575	166.0	46.1	41.4	13.3	0.0	0.1	17.1	52.4	18.6	2.1	0.0	0.0	-51.6	-7.9
	Max.	15.5	7.7	859	295.0	70.0	73.8	34.4	0.1	0.8	23.1	104.0	39.0	4.8	0.1	0.0	-50.4	-7.5
	SD	1.8	0.1	48	26.0	5.8	5.2	5.2	0.0	0.2	1.3	12.9	2.7	0.4	0.0	0.0	0.4	0.1
P6	Av.	13.2	7.1	396	126.7	37.9	17.0	1.7	0.0	0.1	21.1	37.1	9.3	4.6	0.0	0.0	-53.1	-8.0
	Min.	5.7	6.7	253	74.0	21.0	9.3	0.0	0.0	0.1	14.6	24.0	6.0	2.5	0.0	0.0	-54.4	-8.3
	Max.	19.4	7.8	495	163.0	58.7	33.6	6.5	0.1	0.4	29.6	47.7	15.4	14.3	0.2	0.0	-52.0	-7.8
	SD	3.2	0.2	54	17.0	9.4	5.0	1.5	0.0	0.1	3.5	5.5	1.8	1.9	0.0	0.0	0.8	0.1
P7	Av.	13.3	6.9	219	69.5	20.6	8.2	2.4	0.0	0.3	12.9	19.1	5.2	3.2	0.0	0.0	-53.4	-8.2
	Min.	8.0	6.6	163	52.0	10.5	5.6	0.2	0.0	0.1	9.1	14.1	3.4	2.1	0.0	0.0	-54.7	-8.4
	Max.	20.5	7.7	316	91.0	48.5	12.9	7.5	0.1	0.8	18.9	24.2	9.5	23.5	0.1	0.0	-51.2	-7.8
	SD	2.5	0.3	34	9.1	8.0	1.9	1.4	0.0	0.2	2.5	2.5	1.1	3.4	0.0	0.0	1.1	0.2
P9	Av.	12.9	6.9	335	113.6	33.7	9.7	0.4	0.0	0.1	19.2	31.7	6.5	5.3	0.1	0.0	-53.3	-8.1
	Min.	6.6	6.6	203	70.0	15.9	3.9	0.0	0.0	0.2	11.1	19.7	4.2	2.6	0.0	0.0	-54.6	-8.5
	Max.	18.8	7.3	498	167.0	98.8	23.8	4.3	0.0	0.2	31.3	48.9	9.3	63.1	0.3	0.0	-51.3	-7.7
	SD	2.9	0.2	83	28.3	16.7	4.2	0.8	0.0	0.0	5.6	8.3	1.7	9.4	0.1	0.0	1.2	0.3
PZ1	Av.	13.1	7.1	290	95.8	28.3	11.3	0.8	0.0	0.1	16.3	27.3	6.4	4.0	0.1	0.0	-53.7	-8.1
	Min.	7.1	6.7	193	64.0	11.1	5.5	0.1	0.0	0.1	10.7	16.6	4.1	2.5	0.0	0.0	-57.7	-8.5
	Max.	19.1	7.6	413	131.0	82.0	35.1	4.0	0.0	0.2	25.5	43.9	10.4	25.1	0.2	0.0	-49.8	-7.5
	SD	2.8	0.2	73	18.4	15.4	6.8	1.0	0.0	0.0	3.9	7.7	1.9	3.5	0.1	0.0	1.7	0.3
PZ2	Av.	12.9	7.1	491	167.4	40.0	23.4	1.3	0.0	0.1	17.7	48.6	14.9	4.0	0.3	0.0	-52.0	-7.8
	Min.	7.2	6.8	325	114.0	24.2	4.8	0.1	0.0	0.1	13.0	30.6	8.9	2.8	0.0	0.0	-53.2	-8.1
	Max.	21.3	7.4	708	233.0	64.6	52.3	4.8	0.1	0.1	23.3	75.0	22.9	16.3	1.0	0.0	-50.8	-7.4
	SD	3.3	0.1	99	28.5	10.4	12.0	1.4	0.0	0.0	2.5	11.8	3.7	2.1	0.2	0.0	0.6	0.2
PZ3	Av.	13.2	7.3	861	300.0	68.7	62.8	3.2	0.0	0.1	22.8	94.3	29.5	4.5	0.1	0.0	-50.8	-7.4
	Min.	10.3	7.0	804	175.0	62.1	56.9	0.1	0.0	0.1	21.4	48.8	26.2	3.9	0.0	0.0	-51.8	-7.7
	Max.	17.8	7.7	1180	343.0	77.0	71.5	17.1	0.1	0.2	26.1	103.2	38.5	11.0	0.5	0.0	-50.0	-7.1
	SD	2.0	0.2	63	25.8	3.3	2.7	4.4	0.0	0.0	0.9	11.3	1.8	1.2	0.1	0.0	0.5	0.1
PZ4	Av.	13.3	7.2	782	275.1	51.3	57.0	12.3	0.0	0.1	18.0	81.8	32.5	5.0	0.1	0.0	-51.4	-7.6
	Min.	10.5	7.0	425	157.0	28.3	23.8	3.4	0.0	0.1	12.3	32.0	15.8	3.4	0.0	0.0	-53.2	-8.0
	Max.	17.6	7.6	1147	330.0	62.9	69.2	23.7	0.0	0.2	24.6	99.7	47.1	7.0	0.3	0.0	-50.0	-7.4
	SD	1.9	0.2	99	36.0	6.1	7.5	4.6	0.0	0.1	1.9	15.4	4.3	0.5	0.1	0.0	0.7	0.1
PZ5	Av.	12.9	7.3	938	335.9	68.2	76.1	4.7	0.0	0.1	20.0	110.6	33.7	6.9	0.1	0.0	-53.3	-7.9
	Min.	10.2	7.0	530														

924 Table 1: Average, minimum, maximum and standard deviation (SD) values of physico-chemical parameters,  
 925 ions concentrations and  $\delta^{18}\text{O}$ - $\delta^2\text{H}$  data for the 40 campaigns carried out at the 21 samples sites of the  
 926 study zone.

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Sample ID	T (°C)	pH	EC ( $\mu\text{S.cm}^{-1}$ )	HCO <sub>3</sub> <sup>-</sup>	Cl <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	NO <sub>3</sub> <sup>-</sup>	NO <sub>2</sub> <sup>-</sup>	PO <sub>4</sub> <sup>3-</sup>	F <sup>-</sup>	Na <sup>+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>	K <sup>+</sup>	NH <sub>4</sub> <sup>+</sup>	Li <sup>+</sup>
				(mg.l <sup>-1</sup> )												
Allier	5.6	7.5	140	39.0	14.7	7.9	2.3	0.0	0.09	0.1	9.6	10.4	4.3	1.9	0.0	0.0
B2	6.7	7.4	218	62.0	20.3	11.8	1.9	0.0	0.11	0.1	11.5	19.4	6.8	2.4	0.0	0.0
B2bis	8.7	7.1	320	108.0	29.4	15.5	0.7	0.0	0.11	0.2	15.4	30.6	9.0	3.3	0.0	0.0
B3	8.5	7.0	314	113.0	29.3	14.7	0.6	0.0	0.08	0.2	15.7	29.9	8.7	3.5	0.0	0.0
B4	9.1	7.2	326	105.0	30.1	14.3	1.0	0.0	0.12	0.2	16.2	31.1	8.9	3.6	0.0	0.0
B6	10.3	7.0	243	81.0	22.9	11.6	1.4	0.0	0.11	0.2	12.8	22.4	6.9	2.8	0.0	0.0
B7	12.7	7.0	233	81.0	26.1	12.6	1.0	0.0	0.14	0.1	14.4	23.1	6.4	2.9	0.0	0.0
pt3	12.8	x	234	62.0	23.0	12.1	2.2	0.0	0.08	0.2	13.4	20.4	6.0	2.7	0.0	0.0
Monteil	12.6	7.1	872	226.0	57.5	64.3	95.0	0.1	0.15	0.5	12.5	123.8	17.1	11.0	0.0	0.0
P2	10.4	7.0	269	117.0	13.8	8.9	0.1	0.0	0.05	0.2	12.2	19.4	11.3	2.3	0.0	0.0
P3	11.6	7.1	776	243.0	60.4	73.4	27.2	0.0	0.14	0.3	17.7	89.4	29.0	4.4	0.1	0.0
P4	7.9	7.0	308	111.0	29.0	3.5	0.1	0.0	0.07	0.2	14.1	28.4	8.1	2.5	0.9	0.0
P5	11.9	7.2	811	265.0	65.9	66.4	25.5	0.0	0.09	0.3	20.5	95.3	29.1	3.2	0.1	0.0
P6	10.4	6.9	348	127.0	28.7	14.9	1.9	0.0	0.03	0.3	15.8	35.3	9.4	3.7	0.0	0.0
P7	12.5	6.6	245	74.0	25.6	10.8	1.2	0.0	0.08	0.1	14.6	22.9	6.6	2.6	0.0	0.0
P9	11.4	6.7	230	78.0	20.4	9.2	0.2	0.0	0.05	0.2	12.4	22.9	5.0	2.8	0.0	0.0
PZ1	12.6	7.0	197	82.0	16.0	6.4	0.1	0.0	0.08	0.2	11.1	19.0	4.5	2.6	0.0	0.0
PZ2	11.8	7.3	353	136.0	28.9	7.0	0.2	0.0	0.06	0.2	14.5	32.8	9.5	2.9	0.4	0.0
PZ3	13.0	7.1	855	308.0	69.9	61.5	3.0	0.0	0.12	0.2	22.5	98.0	29.4	4.2	0.1	0.0
PZ4	13.2	7.2	771	279.0	52.4	61.5	13.1	0.0	0.09	0.3	17.4	85.9	32.1	5.1	0.0	0.0
pt103	11.2	x	735	282.0	56.6	60.9	0.1	0.0	0.21	0.3	17.8	87.9	31.0	5.1	0.2	0.0
PZ5	13.2	7.3	1002	374.0	70.2	85.8	2.1	0.0	0.18	0.3	21.3	129.0	34.9	7.6	0.1	0.0
PZ6	12.1	7.3	1074	405.0	62.2	107.6	6.1	0.0	0.12	0.4	26.1	150.4	31.3	13.6	0.1	0.0

929

930 Table 2: Physico-chemical parameters and ions concentrations data for the 11/23-11/24/2017 campaign.

931

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1204

1 **List of Figures**

2 Figure 1: a) Location of the Auzon Oxbow; b) Location of the  
3 SOAHAL Observatory with c) a zoom on the Auzon Oxbow (the  
4 two small dashed lines delineate the three distinct sections of the  
5 oxbow: UZ (upstream zone), IZ (intermediate zone) and DZ  
6 (downstream zone)).

7 Figure 2: Time-series of a) Daily precipitation at Sainte Florine  
8 (Météo-France station 43185001, altitude 450 m) and Naussac  
9 (Météo-France station 48105001, altitude 967 m); b) and c)  
10 surface water level at the confluence between Auzon Oxbow and  
11 Allier River; groundwater levels at boreholes b) PZ3 to PZ6 (LB)  
12 and c) PZ1 and PZ2 (RB); d) Allier River discharge at Agnat station  
13 (from Banque Hydro). Low-flow (LF) and high-flow (HF) are  
14 identified with black double arrows while 08/04/2015 and  
15 04/06/2016 events are identified with red lines.

16 Figure 3: Piezometric maps a) of the Low Flow (LF) event of the  
17 04/08/2015 and; b) of the High Flow (HF) event of the  
18 04/06/2016

19 Figure 4: a) EC vs Water T for all the dataset; b) Variations of EC of  
20 Allier River, B2bis (Auzon Oxbow DZ), B4 (Auzon Oxbow IZ), and  
21 B7 (Auzon Oxbow UZ), PZ1 (RB GW), PZ3-PZ4 (LB GW); the grey

22 area highlights the decrease of EC during the April 2016 campaign  
23 in the Auzon Oxbow and PZ4.

24 Figure 5: Chemical water types of the 21 sampling sites given by a  
25 Piper's diagram established from data in  $\text{mg.l}^{-1}$ .

26 Figure 6:  $\text{HCO}_3^-$  vs  $\text{Na}^+/\text{Ca}^{2+}$  ( $\text{mg.l}^{-1}$ ) for Allier River, RB GW (mean  
27 of P2, P4, P6, P7, P9, PZ1 and PZ2), LB GW (mean of P3, P5, PZ3,  
28 PZ4, PZ5 and PZ6), Auzon Oxbow (B2 to B7) and Le Monteil Spring.  
29 The dashed line is an indicative mixing line between Allier River  
30 and LB GW end-members which explain the Auzon Oxbow  
31 signatures.

32 Figure 7: Cartography of EC performed on the 11/23/2017.

33 Figure 8: Piper's diagram established from data in  $\text{mg.l}^{-1}$  of the 21  
34 sampling sites and of the two water arrivals (Pt 3 and 103)  
35 analyzed for the 11/23-24/17 campaign.

36 Figure 9: ERT profile crossing the active paleochannel (blue circle)  
37 upstream from the Auzon Oxbow (orientation SSE-NNW).

38 Figure 10: a)  $\delta^{18}\text{O}$  time-series for Allier River and Auzon Oxbow  
39 (DZ: B2bis; IZ: B4; UZ: B7) from April to November 2017; b)  $\delta^2\text{H}$   
40 and  $\delta^{18}\text{O}$  signatures for Allier River, RB GW (mean of P2, P4, P6,  
41 P7, P9, PZ1 and PZ2), LB GW (mean of P3, P5, PZ3, PZ4, PZ5 and

42 PZ6), Auzon Oxbow (B2 to B7) and Le Monteil spring. Local  
43 Meteoric Water Line (LMWL:  $\delta^2\text{H} = 8 * \delta^{18}\text{O} + 13.7\text{‰}$  by Petelet-  
44 Giraud et al. (2005)) and Global Meteoric Water Line (GMWL:  $\delta^2\text{H}$   
45  $= 8 * \delta^{18}\text{O} + 10\text{‰}$  by Craig (1961)) are also shown for comparison.

46 Figure 11: Conceptual model of the Auzon Oxbow: identification  
47 of its interactions with the Allier River and the alluvial aquifer. The  
48 river supplies its annex by the surface connection at the  
49 downstream confluence and by an underground connection  
50 through the upstream paleochannel (which recharge during HF).  
51 The alluvial groundwater of the left bank was identified to supply  
52 the oxbow during LF especially in its downstream part.





















