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1           **Multiple environmental tracers for a better understanding of water flux**  
2                                   **in a wetland area (La Bassée, France)**

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9  
10 **Abstract**

11  
12 Understanding water exchange between groundwater and streams, or groundwater/surface-  
13 water relationships, is of primary importance for solving conflicts related to water use and for  
14 restoring water ecosystems. To this end, we tested a combination of classic geochemical  
15 tools and isotopic tools on the Bassée study site, located in the alluvial plain of the River  
16 Seine, to see whether they are relevant for tracing multiple and complex  
17 groundwater/surface-water relationships. The Ca/Sr ratio associated with Sr isotopes shows  
18 contrasted values and suggests that infiltration of surface water to groundwater increases  
19 when approaching the Seine. Furthermore, stable isotopes of the water molecule indicate  
20 that water from gravel-pit lakes may infiltrate into groundwater. Tritium and CFC tools  
21 confirmed surface-water influence on the Alluvial and Chalk aquifers. This geochemical  
22 approach, tested on the Bassée site, clearly demonstrates the need of using various  
23 geochemical tools for describing groundwater/surface-water relationships, and can be  
24 conclusively addressed to other case studies for helping decision makers in their  
25 management of natural water resources.

26  
27 **Keywords**

28  $\delta^{18}\text{O}$ ,  $\delta^2\text{H}$ ,  $^{87}\text{Sr}/^{86}\text{Sr}$ ,  $^3\text{H}$ , CFC,  $\text{SF}_6$ , wetland, groundwater, La Bassée, France

29  
30  
31 **1. INTRODUCTION**

32  
33 In studies of hydrological systems over the past few years, new environmental tracers have  
34 been successfully applied, such as strontium, boron and sulphate isotopes, as well as CFCs  
35 and  $\text{SF}_6$  (e.g. Vengosh et al., 2002; Négrel and Pauwels, 2004; Négrel and Petelet, 2005;  
36 Gooddy et al., 2006). New-generation inductively-coupled plasma mass spectrometers (ICP-  
37 MS) have allowed the development of much more precise isotopic measurements for various  
38 elements and a wider use of these tools (e.g. Luais et al., 1997; Marechal et al., 1999; Halicz  
39 et al., 1999; Rehkemper and Halliday, 1999; Galy et al., 2001; Rouxel et al., 2002; Beard et

40 al., 2003; Cardinal et al., 2003; Wombacher et al., 2003). This has provided larger means of  
41 studying hydrological and environmental processes.

42 Recently, the combined use of various geochemical tracers has been successfully applied for  
43 obtaining a better understanding of hydrological systems (Millot et al., 2007; Vengosh et al.,  
44 2007; Bouchaou et al., 2009; Ma et al., 2010) as well as of the interaction between  
45 groundwater and surface water (Oxtobee and Novakowski, 2002; Lamontagne et al., 2005;  
46 Darling et al., 2010). In Millot et al. (2007), the combination of Li, B, Sr and Nd isotopic  
47 systems highlights the complexity of studying geothermal reservoirs, as well as the fact that  
48 using only one isotopic tool could lead to an incomplete interpretation of the origin of water.  
49 For this reason, the use of a multi-tracer approach is relevant and should provide additional  
50 information for the characterization of natural waters in relation to their source.

51 Langman and Ellis (2009), investigating the source of water, showed the usefulness of a  
52 multi-isotope approach in a complex aquifer subject to natural and anthropogenic influences.  
53 The use of traditional geochemical tracers commonly is insufficient for explaining the source  
54 of water in deeper aquifers and the interactions between aquifers; in this case, additional  
55 tools such as  $\delta^{11}\text{B}$  and  $^{87}\text{Sr}/^{86}\text{Sr}$  permit a reinterpretation of the isotopic composition of water,  
56 leading to a conclusive revision of the hydrological model.

57 The complementary information these tracers provide, generally confirms the initially  
58 established conceptual hydrogeological model. But, in some cases all tracers provide the  
59 same information, rendering the use of various tools to be less than cost effective.

60 Occasionally, the information obtained from various geochemical tracers appears to be  
61 contradictory. Though, at first sight, his situation might be considered as a weakness of the  
62 multi-tool geochemical approach, it commonly reveals the strength of the method.  
63 Understanding a system can initially seem complicated, requiring reappraisal of the initial  
64 hypothesis; the use of multiple methods then is the only way of by-passing pre-established  
65 hydrogeological models and of proposing new models that consider the full complexity of  
66 hydrological systems.

67 In the present study, we proposed to use various tracers for evaluating the interconnection  
68 between aquifers and the possible relationships between surface water and groundwater in a  
69 flooded plain. These include tracers of the water cycle ( $\delta^2\text{H}$  and  $\delta^{18}\text{O}$ ), of water-rock  
70 interactions ( $^{87}\text{Sr}/^{86}\text{Sr}$ ), of residence time and transfer mode (CFCs and  $\text{SF}_6$ ), and of  
71 anthropogenic impact ( $^3\text{H}$ ).

72 La Bassée lies south-east of Paris in the alluvial plain of the River Seine. In this area,  
73 hydrological flux between surface- and groundwaters is expected to be complex due to the  
74 presence of several interconnected aquifers below wetlands, ponds, oxbow lakes, and rivers.  
75 The Seine has been channelled since decades and natural flooding is quite reduced in the  
76 area. The Bassée site is the last alluvial plain in the Paris Basin exploited for gravel (Baron

77 and Piketti, 2001). The intensive sand and gravel extraction throughout the alluvial plain  
78 since 40 years has created large borrow-pits that, at the end of the exploitation period, are  
79 filled by ground- and rain-water. The Bassée site is also the major wetland area of the Ile-de-  
80 France region, labelled 'Natura 2000', and part of a Europe-wide network of sites tasked with  
81 the preservation of our natural heritage. It is one of the 87 wetlands of major importance in  
82 France and governmental action plans were established in order to protect the surface water  
83 covering 20% of the plain ([http://natura2000.environnement.gouv.fr /sites/FR1112002.html](http://natura2000.environnement.gouv.fr/sites/FR1112002.html)).  
84 The groundwater here is of great importance as a drinking-water supply and is considered as  
85 a reservoir to be protected for the Paris metropolitan-area water supply (SDAGE,  
86 Management Plan of Seine-Normandy basin). The study area covers 23 km<sup>2</sup> of the  
87 downstream part of the alluvial plain. Previous hydrogeological studies (Mégnién, 1965;  
88 Sogreah, 2004; Armines, 2005) using classical hydrogeological investigation methods  
89 (water-level monitoring, geology, geophysics, geotechnics, and modelling) left uncertainties  
90 on the magnitude of the relations between deep and alluvial aquifers, on the possible  
91 hydraulic connections between deep aquifers and the river, and on the extent of the  
92 relationships between the River Seine and shallow aquifers.  
93 The scope of this study was to improve the hydrological understanding of the system through  
94 the use of multiple geochemical tools, in order to arrive at a better protection of this floodplain  
95 from qualitative and quantitative points of view. To this end, three different types of water  
96 relationships had to be evaluated in the alluvial plain: Chalk and Alluvial groundwater  
97 connections, groundwater (Chalk and Alluvial) and river water relationships, and the relation  
98 between other surface waters (oxbow lakes, ponds, gravel pit lakes) and groundwater. The  
99 alluvial plain in the past having been subject to periodic flooding by the Seine and today  
100 being intensively exploited for sand and gravel extraction, the existing surface water is of  
101 particular ecological and hydrological importance in the studied area.

102

## 103 **2. CHARACTERISTICS OF THE BASSÉE SITE**

104 The Bassée site, south-east of Paris, is of major importance for the drinking-water supply of  
105 Paris and surroundings. The site lies in the large Seine floodplain, delimited upstream by  
106 Bray-sur-Seine and to the west by the Montereau-Fault-Yonne at the junction between the  
107 rivers Seine and Yonne (Fig. 1). In view of its numerous ponds, canals and river arms, the  
108 Bassée plain was included in the "Natura 2000" program.

109 Sand and gravel exploitation and agriculture are the main economic activities in the area.  
110 Three aquifers are interconnected: i) the Alluvial aquifer of the River Seine located within the  
111 whole studied area, ii) the mainly unconfined Chalk aquifer below the alluvial one, and iii) the  
112 Tertiary calcareous formations in the northern part of the area (Fig. 2). The Alluvial and Chalk  
113 aquifers discharge into the Seine (Weng et al., 1999; Vernoux et al., 2004). Groundwater

114 within the Alluvial aquifer circulates following the Seine-flow direction, while groundwater flow  
115 in the Chalk aquifer is south-east to north-west. This geometry induces most probably a  
116 connection between the Chalk and Alluvial aquifers, with direct or indirect (by drainage) flow  
117 of the Chalk aquifer into the Alluvial layers. The very low regional slope created various  
118 meanders that have led to an important and heterogeneous Alluvial aquifer. The water-level  
119 map (Mégnién, 1965) indicates hydraulic continuity between these two aquifers. The Chalk  
120 aquifer is considered as a major component of Alluvial aquifer recharge.

121 In the northern part of the study area, the chalk formations are becoming less permeable and  
122 the groundwater is sometimes in semi-oxic or anoxic conditions. The Tertiary aquifer is  
123 located only in the northern part of the Seine floodplain and is a multilayer calcareous and  
124 marly calcareous aquifer, which locally may recharge the alluvial layers. Thus, recharge of  
125 the Alluvial aquifer occurs directly from precipitation, or through the other aquifers of the  
126 studied site. Natural Seine channels and spaces left by sand and gravel pits form numerous  
127 overflowing areas. During high-water periods, river water infiltration may be possible.

128 It is estimated that about 100 lakes were formed by sand and gravel extraction in the lowest  
129 part of the Bassée plain. After closure of the gravel pits, the space left is filled with low-  
130 permeability material such as clay and silt from recent alluvial deposits, and rapidly reaches  
131 equilibrium with the Alluvial and Chalk groundwater. These gravel-pit lakes are believed to  
132 have very low surface-groundwater exchanges (Schanen et al., 1998).

### 133 **3. MATERIAL AND METHODS**

#### 134 **3.1 Sampling procedures**

135 Two sampling campaigns were carried out in June 2007 during the high water period and in  
136 November 2007 during a low water period. Sampled were 7 locations in the Chalk (noted  
137 Sc), and 12 locations in the alluvial aquifers (noted Sa), the Seine upstream at Bray-sur-  
138 Seine and downstream just before the confluence of the Rivers Seine and Yonne. Sampling  
139 was realised using 6" piezometers drilled in 2002. The complete technical description (total  
140 depth, depth to groundwater, lithology, depth to screens,...) is available and allowed to  
141 select only the piezometers exploiting a unic geological formation (Chalk or Alluvial). In  
142 addition, two gravel-pit lakes at La Tombe and Bazoches-lès-Bray and a well located at La-  
143 Chapelle-sur-Oreuse in the Chalk aquifer upstream from the Bassée alluvial plain were  
144 sampled in November 2007 (Fig. 1). A complementary sampling campaign took place in  
145 July 2008. Tritium analyses were carried out on water of all groundwater points sampled in  
146 2007 and the Seine at Bray-sur-Seine.

147 The analyses of major chemical elements and stable water isotopes ( $\delta^2\text{H}$ ,  $\delta^{18}\text{O}$ ),  $^3\text{H}$ ,  
148  $^{87}\text{Sr}/^{86}\text{Sr}$ , were completed by the determination of apparent groundwater ages using CFCs

149 and SF<sub>6</sub>.  
150 The boreholes were sampled after pumping at least three purge volumes and stabilizing the  
151 chemical groundwater parameters, such as pH and conductivity. Samples for cation and  
152 <sup>87</sup>Sr/<sup>86</sup>Sr determinations were kept in polyethylene bottles after acidification with nitric acid.  
153 Raw water samples of 50 ml and 1 litre in HDPE bottles were used for δ<sup>2</sup>H, δ<sup>18</sup>O and <sup>3</sup>H  
154 analyses. Glass sampling bottles of 500 ml were used for CFC and SF<sub>6</sub> analyses (IAEA,  
155 2006).

### 156 **3.2. Analytical methods**

157 Concentrations were measured on water samples by inductively coupled plasma-atomic  
158 emission spectrometry (ICP-AES) for Ca<sup>2+</sup>, Na<sup>+</sup>, K<sup>+</sup> and Mg<sup>2+</sup>, and by ion chromatography for  
159 Cl<sup>-</sup>, NO<sub>3</sub><sup>-</sup>, SO<sub>4</sub><sup>2-</sup> and PO<sub>4</sub><sup>2-</sup> (uncertainty for both methods 5-10%). Anion analyses were done  
160 by ion chromatography (model DX120, Dionex®), cations by Inductively Coupled Plasma  
161 Atomic Emission Spectroscopy (ICP-AES; Ultima-2 model, Jobin Yvon®). The accuracy of  
162 both techniques was around 5-10% depending upon the concentration.

163 Sr concentrations were measured by inductively coupled plasma mass spectrometry (ICP-  
164 MS) (uncertainty 5%). Alkalinity was determined by HCl titration and Gran's method.  
165 Strontium for isotopic analysis was separated using an ion-exchange column (Sr-Spec resin).  
166 Procedural blank levels were lower than 0.5 ng. The <sup>87</sup>Sr/<sup>86</sup>Sr ratio was measured using a  
167 Finnigan MAT 262 multiple collector mass spectrometer. Sr isotopic ratios were normalized  
168 to <sup>87</sup>Sr/<sup>86</sup>Sr=0.1194. Average uncertainties on individual <sup>87</sup>Sr/<sup>86</sup>Sr measurements were 8.10<sup>-6</sup>  
169 (at 2σ level). International reference NIST-NBS987 measurements yielded <sup>87</sup>Sr/<sup>86</sup>Sr=  
170 0.710238±22 (2σ; N=18). Isotopic ratios of both O and H are given in per mil (‰) *versus*  
171 VSMOW (Vienna Standard Mean Ocean Water) reference material in the usual δ-scale  
172 defined as δ<sub>sample</sub> ‰ = {(R<sub>sample</sub>/R<sub>standard</sub>)-1}\*1000, where R is the <sup>2</sup>H/<sup>1</sup>H and <sup>18</sup>O/<sup>16</sup>O atomic  
173 ratios. O and H isotopic composition of water was measured with a Finnigan MAT 252 mass  
174 spectrometer with an uncertainty of ±0.1‰ and ±0.8‰ for δ<sup>18</sup>O and δ<sup>2</sup>H, respectively.

175 Samples for tritium activity measurements were collected in one litre polyethylene bottles.  
176 Analyses were done by direct liquid scintillation counting. The detection limit was 10 TU  
177 (Tritium Unit with 1 TU equal to 1 tritium atom in 10<sup>18</sup> hydrogen atoms). All isotopic analyses  
178 were carried out by the BRGM Geochemistry Laboratory.

179 Samples for CFC and SF<sub>6</sub> were collected in 500 mL glass bottles. To avoid any air  
180 contamination, each bottle was kept in a water-filled metal box. A simplified sample collection  
181 method described by IAEA (2006) was applied. The analyses were performed by gas  
182 chromatography with an electron-capture detector after pre-concentration using the purge-  
183 and-trap technique developed by Spurenstofflabor, Wachenheim (Germany). The detection  
184 limit was close to 10<sup>-4</sup> pmol, allowing the measurement of CFC concentrations down to

185 0.01 pmol L<sup>-1</sup> and SF<sub>6</sub> concentrations to 0.1 fmol L<sup>-1</sup>. The reproducibility was about ±5% for  
186 water samples.

## 187 **4. RESULTS**

### 188 **4.1 Chemical composition of groundwater**

189 Physico-chemical parameters (Table 1) indicate that groundwater conditions in the northern  
190 part of the studied area, on the right bank of the Seine, are mainly semi-oxic. Eh is <200 mV  
191 NHE (normal hydrogen electrode) for six wells in the Alluvial and Chalk aquifers. In addition,  
192 the NO<sub>3</sub> concentration below the detection limit indicating possible denitrification for various  
193 points compatible with semi-oxic conditions observed in part of the aquifer. Surface- and  
194 groundwaters are of the Ca-HCO<sub>3</sub> type (Fig. 3). Water from one well, Sa26, is of the Ca-SO<sub>4</sub>  
195 type. Water in well Sc13 has very low SO<sub>4</sub> concentrations, representing the more anoxic  
196 conditions and possible sulphate reduction.

197 Binary diagrams (Fig. 4a) confirm an excess of sulphate compared to chloride from rainfall  
198 origin. All surface- and groundwaters fall above the theoretical dilution line for sea water.  
199 Sulphate may originates from evaporates, but another possible source is gypsum for soil  
200 improvement, or fertilizers. In Figure 4b some points are also clearly enriched in chloride  
201 compared to sodium ions. As local rocks are evaporite free, potential chloride sources are  
202 rainfall and Manmade ones. Around Paris, Cl concentrations in precipitation are close to  
203 0.15 mol/L (Mégnyen, 1979). Considering an average enrichment factor (F) estimated by  
204  $\text{Rainfall}_{(\text{mm yearly average})}/(\text{R-Evapotranspiration process}_{(\text{mm yearly average})})$  of 1.5, chloride  
205 concentrations up to 0.23 mmol/L are from rainfall origin.

206 The anthropogenic impact on surface- and groundwater is important in the Bassée plain  
207 where agriculture is the main economical activity, even if gravel extraction gains on cultivated  
208 lands. On a NO<sub>3</sub> vs. Cl diagram (Fig. 5) both groundwater from shallow (Alluvial) and deep  
209 (Chalk) aquifers present nitrate concentrations over 25 mg/L (0.4 mmol/L) and up to  
210 83.1 mg/L (1.34 mmol/L; Sa21). Nitrate concentrations below the detection limit of 0.5 mg/L  
211 and chloride contents over 0.23 mmol indicate possible denitrification processes for these  
212 waters in wells Sa26, Sc09, Sc13, Sc16, SC22, ScH4, Sa16 and Sa38 (only for the  
213 November campaign). In addition, the gravel-pit lakes have very low nitrate concentrations  
214 (<0.5 and 2.8 mg/L or <0.01 and 0.05 mmol/L).

215 Intense pressure from agriculture is also reflected in groundwater by the presence of four  
216 pesticides in 116 analysed samples, which were detected at concentrations above the  
217 detection limits. These pesticides and degradation molecules are atrazine (max. 0.091 mg/L  
218 in the Voulzie River), deethylatrazine (max. 0.3 mg/L in Sc09), glyphosate (max. 5.59 mg/L in  
219 Sa37) and aminomethylphosphonic acid, AMPA (max. 2.52 mg/L in Sa21). Atrazine has not  
220 been used in this area since 2003. Glyphosate has both agricultural and non agricultural  
221 uses, which makes its origin difficult to identify.

222 Both x vs. y and Piper diagrams highlight a similar chemistry for both Alluvial and Chalk  
223 groundwaters. In addition, the chemistry of the Seine and Voulzie is not very different from  
224 that of groundwater.

225

#### 226 **4.2 Strontium isotopes**

227 In the Bassée flood plain area, Ca vs. Sr shows a good correlation whereas the NO<sub>3</sub> vs. Sr  
228 correlation is weak, indicating a dominant lithological origin for Sr (Figs. 6a and 6b). Sr and  
229 the <sup>87</sup>Sr/<sup>86</sup>Sr ratio may therefore be controlled only by water-rock interaction in the Bassée  
230 flood plain, as anthropogenic input of Sr can be neglected.

231 The strontium-isotope range observed in this study agrees with values expected for Jurassic  
232 carbonate rock (<sup>87</sup>Sr/<sup>86</sup>Sr = 0.7067 to 0.7078) and Cretaceous Chalk (<sup>87</sup>Sr/<sup>86</sup>Sr = 0.7072 to  
233 0.7080) (Koepnick et al., 1985, 1990). Furthermore, values measured in this study for the  
234 Chalk aquifer are compatible with those acquired by Négrel and Petelet-Giraud (2005) for  
235 this aquifer in the Somme Basin, north of Paris. Nevertheless, values measured in this study  
236 are globally higher than those documented in the previously cited article. This result implies  
237 the contribution of other Sr sources in addition to carbonate dissolution. The hypothesis of a  
238 strontium contribution from anthropogenic origin was rejected because of the low Sr  
239 concentrations observed (<8 µmol/L) and the lack of significant correlation between Sr  
240 concentrations and nitrate (Fig. 6b) or chloride concentrations (not shown here). On a  
241 <sup>87</sup>Sr/<sup>86</sup>Sr vs. 1/Sr (Fig. 7a) diagram, samples plot globally in a triangle. In this classic diagram,  
242 such a distribution suggests that, at least, three sources of dissolved Sr must explain the  
243 ground- and surface-water composition. One end-member should display low <sup>87</sup>Sr/<sup>86</sup>Sr  
244 values and high Sr concentrations (End-member 1). Another end-member is expected to  
245 have high <sup>87</sup>Sr/<sup>86</sup>Sr values and intermediate Sr concentrations (End-member 2). A third end-  
246 member would display low <sup>87</sup>Sr/<sup>86</sup>Sr values and low Sr concentrations (End-member 3). End-  
247 member 1 displays a Sr concentration and Sr-isotope composition close to the composition  
248 of the Sa26 sampling point (<sup>87</sup>Sr/<sup>86</sup>Sr = 0.70792 and 0.70796; 7.51 and 7.19 µmol/L) and  
249 compatible with a Sr contribution from carbonate dissolution. End-member 2 is close to the  
250 Sc22 and Sa37 sampling points, both of which display the highest <sup>87</sup>Sr/<sup>86</sup>Sr and Ca/Sr ratios  
251 measured in this study (Fig. 8). The Ca/Sr ratio was demonstrated elsewhere to be a good  
252 tool for tracing contrasting lithological origins (Brenot et al., 2008). As there is no correlation  
253 between <sup>87</sup>Sr/<sup>86</sup>Sr (or for the Ca/Sr ratio) and the NO<sub>3</sub> concentration (index of anthropogenic  
254 origin), End-member 2 most probably has a lithological origin. Nevertheless, the <sup>87</sup>Sr/<sup>86</sup>Sr and  
255 Ca/Sr ratios measured for the Sc22 and Sa37 sampling points (defining End-member 2) are  
256 much higher than expected values for local carbonate rock (as discussed above). A similar  
257 deviation towards a radiogenic composition (higher <sup>87</sup>Sr/<sup>86</sup>Sr values) was earlier observed  
258 locally in the Seine Basin (Roy et al., 1999; Brenot et al., 2008), and for the Chalk aquifer in



259 the Somme Basin (Négrel and Petelet-Giraud, 2005). In these cases, the authors suggested  
260 that radiogenic Sr might derive in part by thin marly-clayey beds in carbonate rock through  
261 ion exchange or desorption of Sr, or by dissolution of the potential dolomitic part of carbonate  
262 rock with a more radiogenic isotopic signature. End-member 3 is close to the composition of  
263 Seine water, water from gravel-pit lakes and the Sa48 and Sc13 sampling points.  
264 Furthermore, the Sr-isotope composition of Seine water (Roy, 1996) falls between 0.70777  
265 and 0.70793, close to the composition expected for End-member 3. Thus, End-member 3  
266 could potentially reflect a contribution of dissolved elements in surface water. Water in the  
267 Voulzie River has a different Sr isotopic signature compared to that of the Seine (Fig. 7) and  
268 water from gravel-pit lakes, which could be explained by significant differences in water-rock  
269 interaction. Indeed, the Voulzie River flows through Early Tertiary layers composed of clay  
270 and organic matter, whereas the Seine above the Bassée floodplain mainly flows over  
271 carbonate rock (Roy et al., 1999). The Chalk aquifer sampled upstream also has a quite  
272 different Sr-isotope signature compared to the Chalk aquifer sampled in the Bassée  
273 floodplain (Fig. 7).

274 On a  $^{87}\text{Sr}/^{86}\text{Sr}$  vs. Ca/Sr diagram (Fig. 7b), a positive correlation is seen between  $^{87}\text{Sr}/^{86}\text{Sr}$   
275 values and the Ca/Sr ratio for all sampling points. The lowest Sr-isotope composition and  
276 Ca/Sr ratio in this study are in the Seine ( $^{87}\text{Sr}/^{86}\text{Sr}=0.70793$  to  $0.70778$ ; Ca/Sr=424 to 964),  
277 whereas the highest Sr-isotope compositions and Ca/Sr ratios occur in groundwater at the  
278 Sc22 and Sa37 sampling points ( $^{87}\text{Sr}/^{86}\text{Sr}=0.70832$  to  $0.70858$ ; Ca/Sr=1103 to 1253).  
279 Based on only  $^{87}\text{Sr}/^{86}\text{Sr}$  values, and 1/Sr and Ca/Sr ratios (Fig. 7), one cannot discriminate  
280 the groundwaters of the Alluvial and Chalk aquifers sampled in the Bassée floodplain.

#### 281 **4.3 Tritium and CFC data**

282 The trends of CFCs and SF<sub>6</sub> used as input functions in air correspond to those of the Mace  
283 Head (Ireland) station from the ALE/GAGE/AGAGE program (available from  
284 [cdiac.esd.ornl.gov/ftp/ale\\_gage\\_Agage/](http://cdiac.esd.ornl.gov/ftp/ale_gage_Agage/); Prinn et al., 2000), the closest survey station to the  
285 Bassée site. Apparent groundwater ages were evaluated by using Excel® programs for CFC  
286 developed by the International Atomic Energy Agency (IAEA, 2006). The recharge date was  
287 determined by comparing the calculated partial pressure of CFCs and SF<sub>6</sub> in solubility  
288 equilibrium with the water sample, with historical CFC concentrations in local air. The  
289 equilibrium concentration of CFCs in groundwater depends on the air pressure (i.e. altitude)  
290 and temperature in the saturated zone. Recharge temperatures used are the temperature of  
291 groundwater at high-water-stage sampling time. The mean altitude of recharge is close to  
292 55 m, the average altitude of the alluvial plain. The uncertainty in recharge temperatures and  
293 recharge elevations is respectively maximum 1°C and 50 meters.

294 CFC-11, CFC-12, CFC-113, and SF<sub>6</sub> were systematically measured for groundwater dating.  
295 For five sampling points, Sa26, Sa38, Sa48, Sc16 and ScH4, semi-anoxic conditions most

296 probably caused a degradation of CFCs (Horneman et al., 2008), in which case SF<sub>6</sub> was  
297 then used for dating the water, this element being less sensitive to microbial degradation.  
298 All water samples could be dated at least once. Determination of apparent water ages using  
299 CFC and SF<sub>6</sub> (Plummer and Busenberg, 2000) was done by applying a binary mixing model  
300 considering old water before 1950 (CFC-free) and young water with an age between 1985  
301 and Present. This model was given the best results in “age-dating” (example for CFC-11 and  
302 CFC-113 given in Fig.8). Young-water mixing fractions ranged from 0.20 to 0.99. Results  
303 from the two sampling campaigns are quite similar. The uncertainty in recharge temperature  
304 estimation (about 1°C what is the annual variability of groundwater temperature) is leading to  
305 an uncertainty in mixing ratio of a maximum of 5%. Anthropogenic contamination was  
306 observed in few samples, mainly for CFC-12 and SF<sub>6</sub> possibly due to the proximity of large  
307 urban areas (Oster et al., 1996; Santella et al., 2008).

308 The dissolved gases and age-dating interpretation show a significant differentiation between  
309 the Chalk and Alluvial aquifers. Only two wells (<20%) located in the Alluvial aquifer (Sa5,  
310 Sa20) have a percentage of young water below or equal to 50%, whereas five deep wells  
311 (>71%) tapping the Chalk aquifer (Sc11, Sc16, Sc22, ScH3, ScH4) show a percentage of  
312 young water below 50%. Surprisingly, wells Sc13 and Sc09 in the Chalk aquifer mainly  
313 contain young water, and a direct influence of surface water on these points is expected.  
314 Being far from the River Seine, the influence of ponds or gravel-pit lakes is supposed. The  
315 Alluvial groundwater in 75% of the wells is represented by water with a present (1985-2007)  
316 component below 80%. Therefore, the older and deeper groundwater component is  
317 significant, confirming the initial conceptual hydrogeological model of the Chalk aquifer  
318 discharging into the upper aquifer layers.

319 A few kilometres upstream from the Bassée floodplain, the nuclear power plant at Nogent-  
320 sur-Seine regularly has released tritium into the Seine since its start-up in 1988-1989. Tritium  
321 can thus be used as a radionuclide tracer (Sanchez-Cabeza and Pujol, 1999) of the  
322 infiltration of the Seine to groundwater since then. In the Seine at Bray-sur-Seine, the tritium  
323 concentration measured during the project is quite variable, from 21 TU in July 2008 up to  
324 573 TU in April 2008, reflecting the variable release from the power plant (3.1 to  
325 11.7 TBq/month for the period August 2006-August 2008, data provided by EDF, the  
326 operator). By comparison, the tritium values for Orléans precipitation (closest station at about  
327 120 km from the Bassée site) have on average below 6 TU since 1999 (IAEA/WMO, 2009).

328 Tritium values measured in groundwater are very high (>60 TU) for Sc13, Sa41, Sa48 and  
329 Sa61, and high (>15 TU) for Sc09, indicating a more or less important influence of surface  
330 water on the Chalk and Alluvial aquifers at these points.

#### 331 **4.4. Stable isotopes**

332 The  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  isotope composition of groundwater is -47 to -25‰ and -7.1 to -2.4‰,  
333 respectively (Table 1). In the  $\delta^2\text{H}$  vs.  $\delta^{18}\text{O}$  diagram (Fig. 9), most of the water falls on the  
334 local meteorological line (LML) represented by Orléans station (IAEA/WMO, 2009) with no  
335 significant difference between the Alluvial and Chalk aquifers and the River Seine. The  
336 average annual composition of  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  of the Seine water measured from oct.74 to  
337 sep.76 at Poses (upstream Paris, 200 km far from La Bassée; Conrad et al., 1978) is falling  
338 very closed to the 1996-2010 weighted mean of precipitation collected at Orléans.

339 The most isotopically depleted groundwater is that sampled in the Chalk aquifer upstream  
340 from the Bassée area, which thus can be considered as the Chalk aquifer without influence  
341 by surface and/or alluvial water. Another groundwater sample taken in 2009 at 120 km west  
342 of the Bassée area in the Chalk aquifer of Paris Basin, has a similar isotopic content as that  
343 of the Chalk water sampled at La-Chapelle-sur-Oreuse. River water from the Seine or the  
344 Voulzie shows more enriched values. All other samples may be considered to be a mix  
345 between “pure” groundwater and surface (rainfall and/or river) water from different periods,  
346 and therefore with different isotope contents. Variation of the Seine isotopic composition is  
347 about 1 ‰ (Conrad et al., 1978).

348 Some points in the Alluvial (Sa26, Sa38) and Chalk (Sc13, Sc16) aquifers fall on a line with a  
349 slope of 4.3 that may correspond to isotopic fractionation caused by evaporation  
350 (evaporation lines have a slope between 3.5 and 6 as function of local atmospheric humidity ;  
351 Gat, 1981). To test this hypothesis, we calculated the evaporation line with as starting point  
352 the average weighted  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  values of precipitation in Orléans for the period 1999-  
353 2009, and which would explain the compositions of samples Sa26, Sa38 (Alluvial aquifer)  
354 and Sc13, Sc16 (Chalk aquifer). The calculations show that the two gravel-pit lakes sampled  
355 in November 2007 have a stable-isotope composition falling onto the same evaporation line  
356 and display the most fractionated isotopic composition from all samples in the Bassée  
357 floodplain; here, water renewal is limited and therefore evaporation is expected to be high.  
358 Though to a smaller extent, river water is also evaporated and falls on the same evaporation  
359 line. This clearly indicates that some sampling points in groundwater integrate evaporated  
360 water that could be provided either by gravel-pit lakes or by river water.

## 361 **5. DISCUSSION**

### 362 **5.1. Groundwater-river relationships**

363 Existing models (Mégnyen, 1979; Armines, 2005), consider that the Chalk aquifer supplies  
364 water to the Alluvial aquifer, which then discharges into the Seine. More specific studies  
365 (Chabart et al., 1992) have shown that, locally and occasionally, the River Seine can  
366 influence the Alluvial aquifer.

367 Based on only the major element concentrations, the geochemical composition of  
368 groundwater and surface water cannot be discriminated. Other geochemical tools are thus  
369 needed to reach a better understanding of the potential relationships between rivers and  
370 groundwater.

371 Sr isotopes are known (Négrel and Petelet-Giraud, 2005) to be an interesting tool for  
372 groundwater-surface water relationships. In the Bassée site the Sr ratio contrast observed  
373 between groundwater and surface water confirms its potential use in this context.

374 The spatial distribution of sampling points in the Bassée floodplain allows the construction of  
375 two north-south profiles perpendicular to the Seine. Along these profiles, the Ca/Sr ratio and  
376  $^{87}\text{Sr}/^{86}\text{Sr}$  values (Fig. 10) show a significant decrease, with the lowest values close to the  
377 Seine for the high- and the low-water-stage sampling campaigns. Knowing the Ca/Sr ratio  
378 and  $^{87}\text{Sr}/^{86}\text{Sr}$  values of the Seine water, the concomitant decrease of these two geochemical  
379 tracers suggests an increasing contribution of Seine water to the groundwater close to the  
380 riverbanks. Furthermore, the Ca/Sr ratio (1139) and the Sr isotopic signature  
381 ( $^{87}\text{Sr}/^{86}\text{Sr}=0.70812$ ) of Chalk aquifer groundwater collected at “La Chapelle”, 10 km away to  
382 the north (Fig. 1), are significantly higher than the signatures measured for groundwater  
383 collected closed to the Seine (Sa48, Sa41, Sch3, Sa26, Sa21, Sa20 and Sc16). The Ca/Sr  
384 ratio and Sr isotopic compositions thus clearly show a recharge of the aquifers by surface  
385 water during the high- and low-water stages. Surface water contribution seems to be of the  
386 same importance for both Alluvial and Chalk aquifers. River-water infiltration to groundwater  
387 is possible close to the river banks, and around ponds and gravel-pit lakes.

388 The sampling points located upstream and far from the Seine (Sc22, Sa37, Sc09, Sa61 and  
389 Sa65) have the highest Ca/Sr ratio (930 to 1134) and  $^{87}\text{Sr}/^{86}\text{Sr}$  (0.70817 to 0.70835)  
390 compared to the Seine water composition. At the opposite, sampling points located  
391 downstream of the Bassée alluvial plain and close to the Seine (Sc11, SCH3 and Sa02) have  
392 a Ca/Sr (876 to 916) close to the ratio measured at the upstream Seine station (not all points  
393 fall onto the N-S profiles and therefore cannot be seen in Figure 10).

394 Tritium-content data show that very high (>60 TU) values for Sc13, Sa41, Sa48 and Sa61  
395 and high (>15) values for Sc09 indicate a direct influence of river water on the Chalk and  
396 Alluvial aquifers at these points. For well Sc13, located far from the main stream but close to  
397 a large flooded area, many of the ponds and gravel-pit lakes are most probably fed directly  
398 by the River Seine and the canal parallele to the Seine. Tritium content then indicates the  
399 input of river water into groundwater via a residence period in ponds and gravel-pit lakes. A  
400 quantitative estimation is not possible as tritium input varies throughout the year.

## 401 **5.2 Relationship between groundwater and gravel-pit lakes**

402 Numerous gravel-pit lakes or natural ponds, swamps, oxbow lakes, and other backwaters  
403 exist in the flood plain. Chemical data and  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios do not show significant differences

404 between water from the aquifers and such surface waters. This was expected, as such  
405 waters mostly consist of groundwater.

406 In these water bodies, water renewal is limited and evaporation is quite high. Evaporation of  
407 water before infiltration was highlighted for some wells using the  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  isotope  
408 composition.

409 Most of the lakes were created by gravel extraction, causing a change in the hydraulic  
410 properties of the Alluvial aquifer. It is expected that these artificial holes also facilitate the  
411 infiltration of surface water down to the deeper parts of the aquifers. The high permeability of  
412 the walls suggests that water will mainly infiltrate horizontally into both the Chalk and Alluvial  
413 aquifers.

414 Water sampled at Sc13 in the Chalk aquifer is the most intensively evaporated. Due to the  
415 strong variability in H and O isotope signatures of the gravel-pit lakes (only two of them were  
416 sampled), it is possible that fractionation is even stronger in other superficial water bodies.  
417 The Sc13 water may result from a mixture of surface water with a more fractionated isotopic  
418 signature (higher H and O isotopic signatures) than the two gravel-pit lakes sampled in this  
419 study or the groundwater. The infiltration of surface water to the aquifer is also clearly shown  
420 at sampling points Sa26, Sa38, Sc13 and Sc16 (Fig. 9).

421 Dissolved gases (CFC-11, CFC-12, CFC-113,  $\text{SF}_6$ ) and age-dating interpretation give quite  
422 heterogeneous results. Piezometers Sc13 and Sc09 in the Chalk aquifer mainly contain  
423 young water, and a direct influence of surface water on these points is thus expected. Being  
424 far from the Seine, the influence of ponds or gravel-pit lakes is most likely for these two wells.  
425 However, the recharge functioning is quite complex for Sc09 located in the eastern part of  
426 the study area, far from the Seine and any flooded area. No explanation could be found to  
427 explain the geochemical parameters of groundwater at this point.

### 428 **5.3. Impact of the water dynamics on groundwater quality**

429 An understanding of the hydraulic connections in the Seine floodplain may help in  
430 understanding groundwater contamination. Borrow pits were initiated in the area in the 1970s  
431 and rapidly increase in number. This extraction activity does not seem to have a direct  
432 qualitative impact on the groundwater. Agriculture today occupies 40% of the Bassée plain  
433 as against 46% in 1976 (Fustec et al., 2001). The dominant crops are cereals (wheat, maize,  
434 barley, rape, sunflower) and sugar beets, and diffuse pollution is expected at the study area.  
435 Groundwater contamination can be quite high in the left bank of the Seine. Nitrate  
436 concentrations measured in June and November 2007 were, for 9 wells of the 19 sampled,  
437 over 17 mg/L and up to 83.1 mg/L (Sa21), confirming an anthropogenic impact. For 5 wells  
438 (4 in the Chalk and 1 in the Alluvial aquifer), reducing conditions may have led to  
439 denitrification. Existing data ([www.eaufrance.adès.fr](http://www.eaufrance.adès.fr)) underlines the importance of  
440 contamination of the Alluvial aquifer. Actually, 40% of the wells in the Bassée Alluvial aquifer

441 in the past showed triazine contamination at least once. Pesticide (mainly atrazine and DEA)  
442 and nitrate contamination have also been detected in wells tapping the Chalk aquifer. For the  
443 Water Framework Directive, both groundwater bodies (FRHG006 Alluvial aquifer on the  
444 Bassée site and FRHG209 Chalk aquifer) were classified as having a poor chemical status.  
445 The percentage of young groundwater was compared to nitrate concentrations (Fig. 10). A  
446 positive correlation was observed between the percentage of young water and nitrate  
447 concentrations for water in aerobic conditions, circulating in the Alluvial and Chalk aquifers.  
448 For most sampling points, the more important is the influence of the young groundwater, the  
449 higher are the nitrate concentrations (Fig. 11), whereby the “youngest” groundwater dates  
450 from 1985 up to 2007. In captive parts of the aquifer or around wetlands, the nitrate  
451 concentrations are below the detection limit (0.5 mg/L), most probably due to denitrification  
452 processes (in grey on Fig. 11). Seine water upstream and downstream from the study area  
453 has an average nitrate concentration lower than groundwater (<0.5 mg/L to 35.4 mg/L).  
454 For Sa61, Sa41, Sa48 relatively low nitrate concentrations compared to the apparent CFC  
455 ages may be explained by surface water influence (Fig. 11). In fact, the very high tritium  
456 content in groundwater from these three wells indicates a stronger influence of the Seine on  
457 groundwater, an influence that was also felt in Sc13 and Sc09. At the latter two points, a low  
458 redox potential suggests possible denitrification processes. In Sc09, the nitrate concentration  
459 in November 2007 (74.2 mg/L) and the redox potential (311 mv NHE) are higher than during  
460 the high water period (<0.5 mg/L and 345 mV NHE, respectively). As other chemical  
461 elements have similar concentrations for the high and low water sampling campaigns,  
462 denitrification is the most probable process for explaining major changes for only the NO<sub>3</sub>  
463 concentration.  
464 The two sampled gravel-pit lakes have nitrate concentrations of 2.8 and <0.5 mg/L. Low  
465 nitrate concentrations can be explained by dilution (from rainfall and/or rivers), adsorption by  
466 plants and denitrification processes, as was earlier demonstrated in riparian wetlands  
467 upstream from the present study area (Bendjoudi et al., 2002). Concentrations of other  
468 chemical elements are similar or lower than in river water. Dilution by rainfall input is  
469 probably the most important factor, as Redox conditions may not allow denitrification  
470 processes and there are no or very few plants in the gravel-pit lakes. Previous work (Fuster  
471 et al., 2001) showed that silt deposits at the bottom of the gravel-pit lakes greatly reduce  
472 groundwater exchanges. Evaporation and recharge by precipitation therefore are dominating  
473 factors of the hydraulic balance of these specific surface-water bodies. Infiltration of water  
474 from gravel-pit lakes has a positive influence on groundwater quality. As for river water, the  
475 infiltration of water from gravel pits reduces, at least locally, the nitrate concentration in wells  
476 upstream from these artificial lakes.

## 477 **6. CONCLUSIONS**

478 From the geochemical tools the following conclusions may be drawn:

- 479 • No systematic chemical differentiation exists between the Chalk and Alluvial aquifer  
480 waters. This confirms that the conceptual hydrogeological model is correct at a  
481 regional scale, which considers that Chalk groundwater supplies water to the Alluvial  
482 aquifer. However, at the local scale more complex hydraulic connections exist  
483 between the different water bodies, as was highlighted by using isotope tools and  
484 age-dating. Both the Chalk and the Alluvial aquifers may be influenced by surface  
485 water.
- 486 • Age-dating highlighted the presence of young, i.e. less than 10 years old,  
487 groundwater in the wells Sc09 and Sc13 tapping the Chalk aquifer.
- 488 • The influence of Seine water, direct or indirect through the alluvial deposits, was  
489 shown using tritium and Sr isotope data for Sa41, Sa48 and Sa61.
- 490 • The impact on the aquifer of water stored in the gravel-pit lakes or other natural  
491 shallow lakes, ponds or swamps, was highlighted by using stable-isotope tools. The  
492 evaporation effect was clear on groundwater collected in wells Sc13, Sc16, Sa26 and  
493 Sa38. For Sc13, both a surface-water influence by the Seine through alluvial deposits  
494 and by infiltration from gravel-pit lakes is possible.
- 495 •  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$ , tracers of water-rock interaction processes ( $^{87}\text{Sr}/^{86}\text{Sr}$ , Ca/Sr) and of  
496 water origin ( $^3\text{H}$ ) differentiated the role of the River Seine, gravel-pit lakes (and most  
497 probably other superficial water bodies) in local groundwater recharge. The  
498 geochemical approach provided a spatial characterization of the origin of water and  
499 dissolved elements from surface and groundwater bodies.
- 500 • The geochemical approach tested on this site clearly demonstrates the efficiency of  
501 geochemical tools for describing the relationships between groundwater, river water  
502 and lake water. In addition, it underlined the need of using multiple tools for  
503 understanding a complex water system.
- 504 • The approach described in this paper can be usefully applied to other case studies,  
505 and will help decision makers in the context of natural water management.

506

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648

649 **Figure and table captions**

650 Figure 1 - Map showing the studied area and location of sampling points

651 Figure 2 - N-S synthetic geological profile through the Bassée area

652 Figure 3 - Piper diagram for ground- and surface waters sampled in June and November  
653 2007 in the Bassée floodplain and in one well upstream in the Chalk aquifer

654 Figure 4 -  $\text{SO}_4$  vs. Cl and Na vs. Cl for surface and groundwater sampled in the Bassée plain  
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656 Figure 5 -  $\text{NO}_3$  vs. Cl for surface and groundwater sampled at the Bassée plain in June and  
657 November 2007 and groundwater sampled upstream (Chalk aquifer)

658 Figure 6 - Ca vs. Sr and  $\text{NO}_3$  vs. Sr for surface and groundwater sampled at the Bassée plain  
659 in June and November 2007 and groundwater sampled upstream (Chalk aquifer)

660 Figure 7 -  $^{87}\text{Sr}/^{86}\text{Sr}$  vs. 1/Sr (molar) and  $^{87}\text{Sr}/^{86}\text{Sr}$  vs. Ca/Sr (molar) for surface and  
661 groundwater sampled in the Bassée plain in June and November 2007  
662 and in an upstream well

663 Figure 8 - CFC-11 vs. CFC-113 (in pptv) for groundwater collected in the La Bassée site in  
664 June and November 2007 and piston flow, exponential and binaxy mixing of young water  
665 (recharged in 1985 and 2005) with CFC-free water reference lines

666 Figure 9 -  $\delta^2\text{H}$  vs.  $\delta^{18}\text{O}$  for surface and groundwater collected in the Bassée site in June and  
667 November 2007; local meteoric line and mean weighted values for precipitations at Orléans  
668 (1996-2010), mean of Seine water at Poses (1974-1976) and calculated evaporation line

669 Figure 10 -  $^{87}\text{Sr}/^{86}\text{Sr}$  vs. distance and Sr/Ca vs. distance for groundwater collected in June  
670 and November 2007 along the two north-south profiles

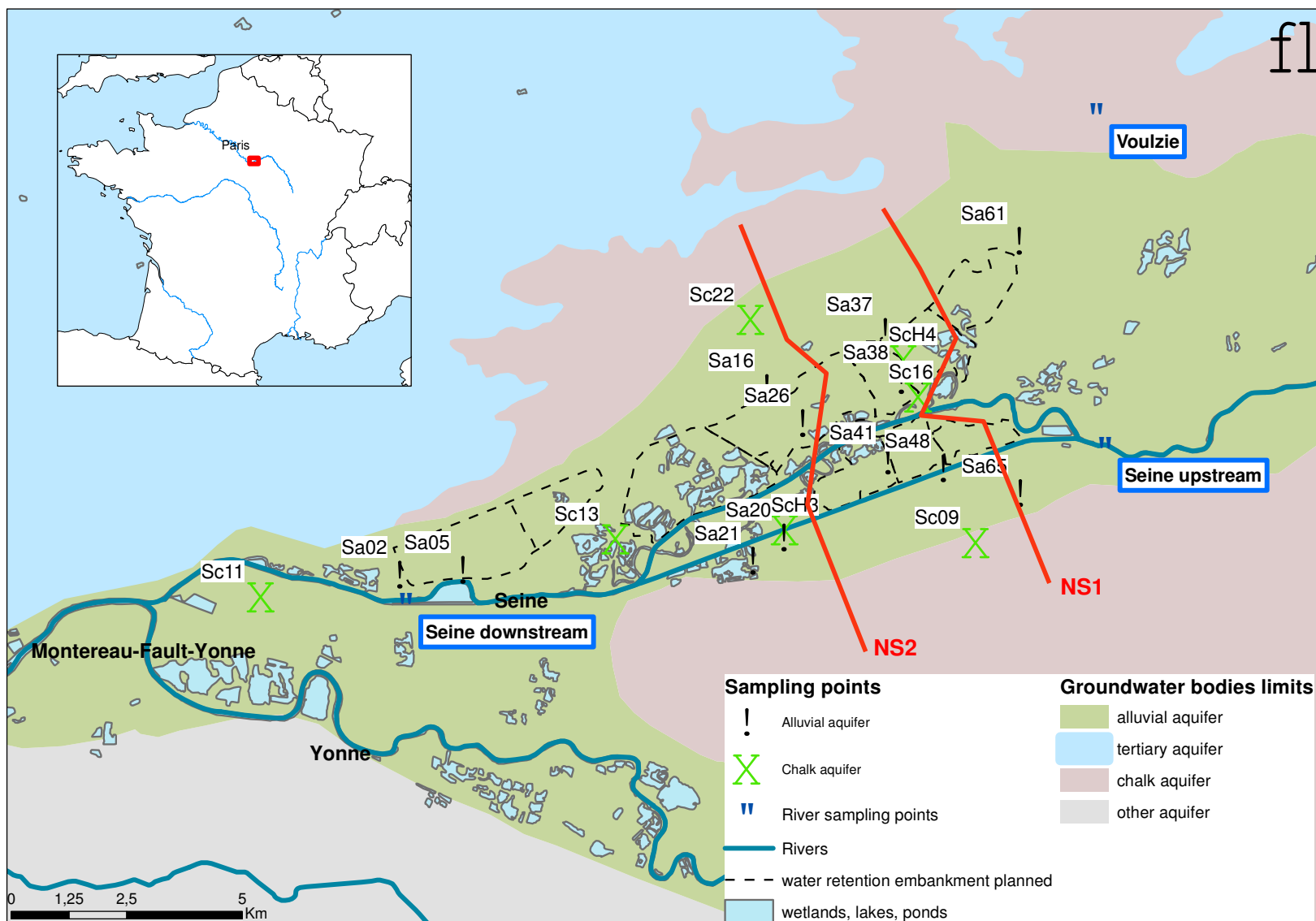
671 Figure 11 -  $\text{NO}_3$  vs. % of young groundwater for groundwater sampled in June and  
672 November 2007 in the Bassée alluvial plain

673

674 Table 1 - Analytical results for June and Novembre 2007 sampling campaign

N°	type	Date	Cond.	Eh(NHE)	Temp.	pH	Ca	Mg	Na	K	HCO <sub>3</sub>	Cl	NO <sub>3</sub>	SO <sub>4</sub>	Sr	Rb	<sup>87</sup> Sr/ <sup>86</sup> Sr	δ <sup>18</sup> O	δ <sup>2</sup> H	
			μS.cm <sup>-1</sup>	mV	°C	μmol/L	μmol/L	μmol/L	μmol/L	μmol/L	μmol/L	μmol/L	μmol/L	μmol/L	μmol/L	μmol/L	μmol/L	μmol/L	‰	‰
<b>June-07 (high flow period)</b>																				
Sa02	Alluvial aquifer	12/06/2007	734	383	11.9	7.1	3671	86	278	49	4607	775	969	723	4.01	0.01	0.708001	-6.4	-42.3	
Sa05	Alluvial aquifer	12/06/2007	643	359	12.3	7.1	3150	136	300	49	4869	541	658	353	3.89	0.00	0.708063	/	/	
Sa16	Alluvial aquifer	12/06/2007	725	250	12.8	7.1	3549	152	513	69	4902	868	161	931	3.40	0.01	0.708152	-6.4	-42.3	
Sa20	Alluvial aquifer	12/06/2007	579	311	12.0	7.2	2746	115	413	90	4721	515	458	214	3.38	0.02	0.707981	-6.7	-45.1	
Sa21	Alluvial aquifer	12/06/2007	578	350	12.5	7.4	2618	66	239	74	3508	617	1332	166	2.67	0.00	0.707940	-6.4	-42.5	
Sa26	Alluvial aquifer	13/06/2007	1135	173	11.7	7.0	6426	222	361	18	5639	606	<DL	3650	7.51	0.00	0.707925	-4.8	-35.7	
Sa37	Alluvial aquifer	13/06/2007	786	358	11.3	7.0	3469	169	983	128	5459	1270	540	510	3.06	0.01	0.708325	-6.6	-43.2	
Sa38	Alluvial aquifer	13/06/2007	668	154	12.0	7.0	3337	123	465	23	5459	676	94	524	3.29	0.00	0.708184	-4.8	-35.7	
Sa41	Alluvial aquifer	13/06/2007	541	351	13.2	7.2	2471	152	339	100	4164	361	276	257	3.34	0.02	0.708042	-6.6	-45.1	
Sa48	Alluvial aquifer	13/06/2007	533	302	15.9	7.3	2349	160	470	72	4066	637	95	323	3.03	0.01	0.707777	-6.5	-44.1	
Sa61	Alluvial aquifer	12/06/2007	860	287	12.1	6.9	4005	387	670	348	7213	901	202	712	3.77	0.00	0.708168	-6.8	-44.0	
Sa65	Alluvial aquifer	13/06/2007	763	375	17.3	7.1	3436	140	465	51	5049	989	989	339	3.56	0.00	0.708246	-6.4	-42.4	
Sc09	Chalk aquifer	13/06/2007	645	345	18.6	7.2	2885	128	474	0	4213	769	<DL	258	3.07	0.01	0.708168	-7	-46.9	
Sc11	Chalk aquifer	12/06/2007	525	386	12.3	7.2	2731	78	487	28	4557	538	432	232	3.09	0.00	0.708119	-6.9	-45.9	
Sc13	Chalk aquifer	12/06/2007	414	105	13.4	7.4	1788	111	313	38	3656	437	<DL	22	2.47	0.00	0.707807	-2.4	-25.2	
Sc16	Chalk aquifer	13/06/2007	682	175	11.5	7.0	3479	189	330	31	5705	462	<DL	715	3.81	0.01	0.708063	-6	-41.8	
Sc22	Chalk aquifer	12/06/2007	700	321	12.5	7.0	3519	103	452	15	5443	854	<DL	352	2.81	0.00	0.708582	-6.7	-44.5	
ScH3	Chalk aquifer	12/06/2007	500	282	14.7	7.3	2259	144	270	41	3787	352	626	163	2.82	0.00	0.707798	-6.8	-46.0	
ScH4	Chalk aquifer	13/06/2007	733	162	11.8	6.9	3451	193	643	33	5721	814	<DL	594	3.39	0.00	0.708156	-6.8	-45.1	
Seine Amont	River	13/06/2007	536	344	23.5	8.2	2334	165	591	66	3607	732	361	426	3.25	0.02	0.707728	-6.3	-43.6	
Voulzie	River	13/06/2007	661	364	18.7	8.2	2339	165	535	64	3689	718	368	425	2.24	0.00	0.708282	-6.6	-44.0	
Seine Aval	River	13/06/2007	538	391	23.1	8.2	3027	210	604	79	4836	941	600	363	3.14	0.00	0.707749	-6.2	-42.0	
<b>October-07 (low flow period)</b>																				
Sa02	Alluvial aquifer	06/11/2007	736	271	12.9	7.1	3641	74	243	49	4770	868	985	783	4.16	/	0.708019	-6.5	-41.3	
Sa05	Alluvial aquifer	06/11/2007	640	265	13.5	7.3	3137	115	257	51	5016	552	650	354	3.89	/	0.708108	-6.7	-42.8	
Sa16	Alluvial aquifer	06/11/2007	735	243	13.5	7.2	3456	160	296	28	5574	501	<DL	760	4.16	/	0.708242	-6.3	-41.5	
Sa20	Alluvial aquifer	06/11/2007	563	378	12.8	7.5	2626	95	343	90	4656	510	571	177	3.32	/	0.708002	-6.9	-45.7	
Sa21	Alluvial aquifer	06/11/2007	575	301	14.2	7.6	2656	58	200	64	3459	668	1340	166	2.72	/	0.707974	-6.4	-42.3	
Sa26	Alluvial aquifer	06/11/2007	1095	139	13.2	7.2	6095	189	335	18	5410	631	<DL	3373	7.19	/	0.707964	-4.7	-34.2	
Sa37	Alluvial aquifer	06/11/2007	818	302	13.5	7.4	3651	156	961	125	5705	1693	518	534	3.31	/	0.708349	-6.6	-42.5	
Sa38	Alluvial aquifer	07/11/2007	661	196	12.9	7.1	3257	119	430	28	5393	735	<DL	519	3.20	/	0.708231	-4.3	-34.3	
Sa41	Alluvial aquifer	07/11/2007	593	330	14.2	7.3	2698	148	330	113	4803	400	353	404	3.73	/	0.708066	-6.9	-45.6	
Sa48	Alluvial aquifer	07/11/2007	425	276	15.6	7.5	1900	119	287	51	3492	414	13	243	2.52	/	0.707802	-6.3	-43.0	
Sa61	Alluvial aquifer	06/11/2007	841	306	13.2	7.1	3868	296	587	315	6951	1090	192	575	3.55	/	0.708195	-6.8	-44.5	
Sa65	Alluvial aquifer	07/11/2007	678	325	12.8	7.4	3057	119	504	64	4459	1096	1129	177	3.28	/	0.708244	-6.6	-44.5	
Sc09	Chalk aquifer	07/11/2007	614	311	12.5	7.5	2890	107	422	0	4033	893	1197	212	3.11	/	0.708177	-7.0	-46.6	
Sc11	Chalk aquifer	06/11/2007	565	282	12.0	7.2	2678	70	387	31	4672	603	484	217	3.05	/	0.708127	-6.9	-46.2	
Sc13	Chalk aquifer	06/11/2007	418	88	14.9	7.6	1798	103	300	38	3885	462	<DL	21	2.49	/	0.707820	-2.4	-24.7	
Sc16	Chalk aquifer	06/11/2007	679	146	12.7	7.3	3579	148	413	51	5180	910	519	809	3.37	/	0.708015	-6.2	-41.5	
Sc22	Chalk aquifer	06/11/2007	645	283	12.2	7.3	3252	78	370	18	5410	701	340	259	2.81	/	0.708476	-6.9	-44.8	
ScH3	Chalk aquifer	07/11/2007	509	378	12.8	7.3	2292	128	239	41	3770	383	653	166	2.79	/	0.707837	-6.8	-45.5	
ScH4	Chalk aquifer	06/11/2007	740	149	12.2	7.3	3514	165	604	33	5836	966	<DL	687	3.08	/	0.708259	-6.9	-45.8	
Seine Upstream	River	07/11/2007	455	338	10.1	8.3	1980	144	322	54	3443	456	224	257	2.69	/	0.707783	-6.1	-42.4	
Voulzie	River	07/11/2007	674	329	8.7	8.0	2868	185	600	100	4721	1082	571	315	2.31	/	0.708247	-6.6	-43.9	
Seine Downstream	River	07/11/2007	443	341	10.5	8.4	1925	140	309	54	3295	451	219	250	2.61	/	0.707790	-6.1	-41.9	
Bassin Amont	Ponds	07/11/2007	287	320	9.1	8.0	1012	119	322	64	1754	459	45	190	2.39	/	0.707933	-4.9	-35.8	
Bassin Aval	Ponds	07/11/2007	346	348	10.2	8.2	1384	123	339	43	2787	558	<DL	63	2.32	/	0.707816	-3.7	-31.2	
AEP La Chapelle	Chalk aquifer	07/11/2007	522	387	12.0	7.3	2379	62	274	77	3820	454	811	97	2.09	/	0.708119	-7.1	-46.5	
<b>Sampling of the Seine River at Bray/Seine on a monthly basis</b>																				
Seine at Bray/Seine	River	13/06/2007	536	344	23.5	8.2	2334	165	591	66	3607	732	361	426	3.25	/	/	/	/	
Seine at Bray/Seine	River	03/08/2007	402		20.9	8.2	1910	144	300	43	3180	355	240	242	2.23	/	/	/	/	
Seine at Bray/Seine	River	21/09/2007	386	458	16.2	8.3	1796	144	322	46	3098	397	227	214	2.23	/	/	/	/	
Seine at Bray/Seine	River	06/11/2007	455	337	10.1	8.3	1980	144	322	54	3443	456	224	257	2.69	/	/	/	/	
Seine at Bray/Seine	River	04/01/2008	548	599	6.1	8.3	2673	152	326	54	4230	499	458	294	3.26	/	/	/	/	
Seine at Bray/Seine	River	15/02/2008	545	617	6.5	8.4	2676	148	330	49	4197	544	463	286	3.17	/	/	/	/	
Seine at Bray/Seine	River	25/03/2008	492	549	7.2	8.2	2377	136	235	49	4328	327	397	183	2.66	/	/	/	/	
Seine at Bray/Seine	River	30/04/2008	509	573	13.3	8.1	2387	132	239	38	4246	456	329	206	3.56	/	/	/	/	
Seine at Bray/Seine	River	27/05/2008	506		16.7	8.1	2444	144	378	51	3967	580	405	279	3.92	/	/	/	/	

Figure



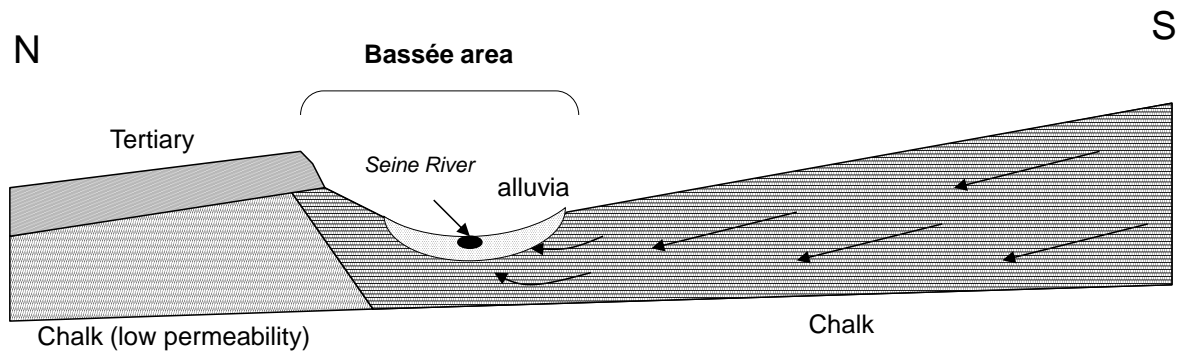


Figure 2 : Synthetic geological profile of the La Bassée area

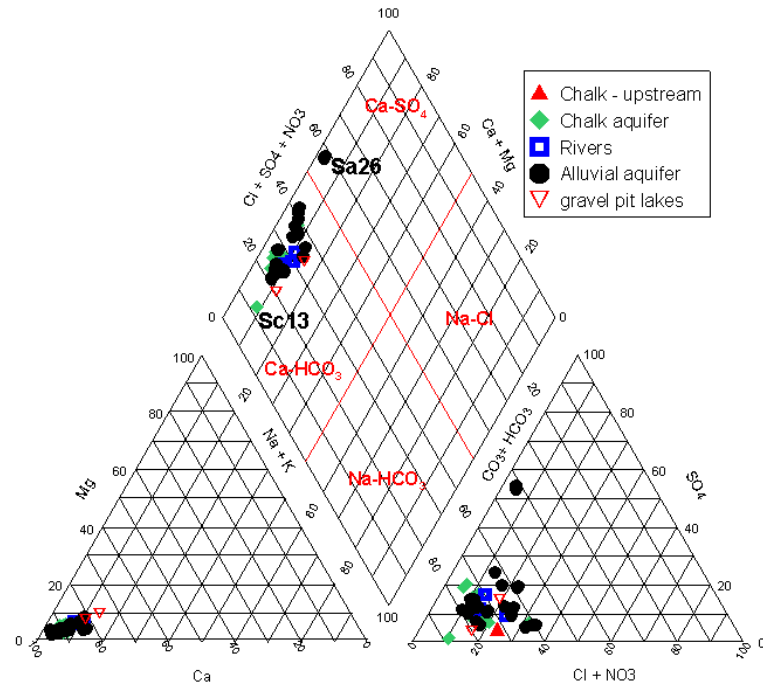


Figure 3 : Piper diagram for ground and surface water sampled in June and November 2007 in the La Bassée floodplain and one well groundwater upstream (chalk aquifer)

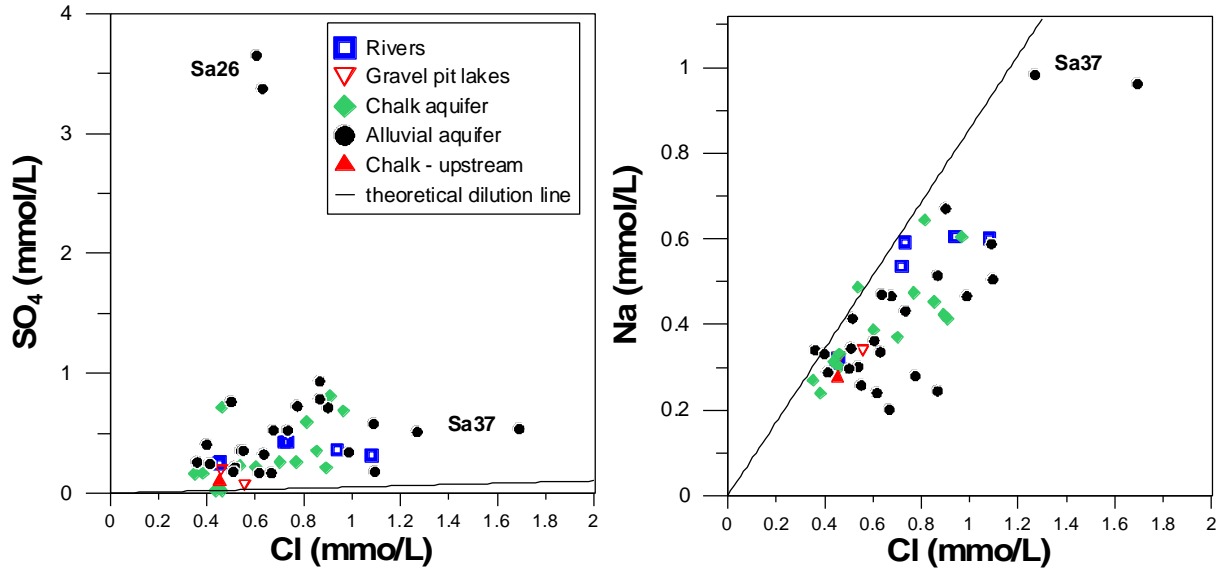


Figure 4 : SO<sub>4</sub> vs. Cl and Na vs. Cl for surface and groundwater sampled at the La Bassée plain in June and November 2007 and groundwater sampled upstream (Chalk aquifer)



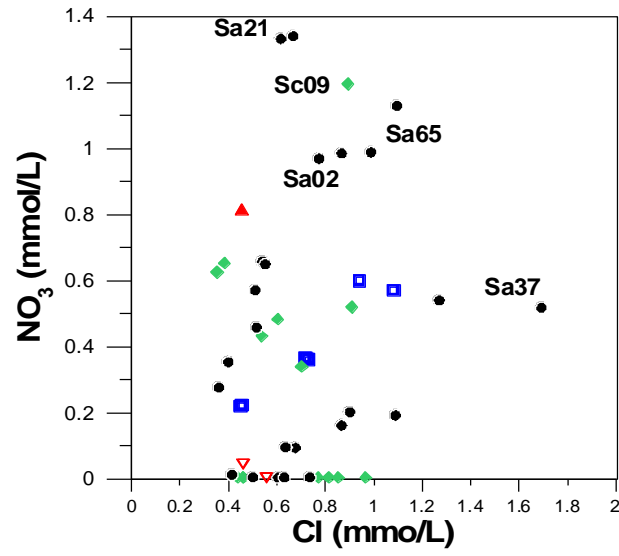


Figure 5 : NO<sub>3</sub> vs. Cl for surface and groundwater sampled at the La Bassée plain in June and November 2007 and groundwater sampled upstream (chalk Aquifer)

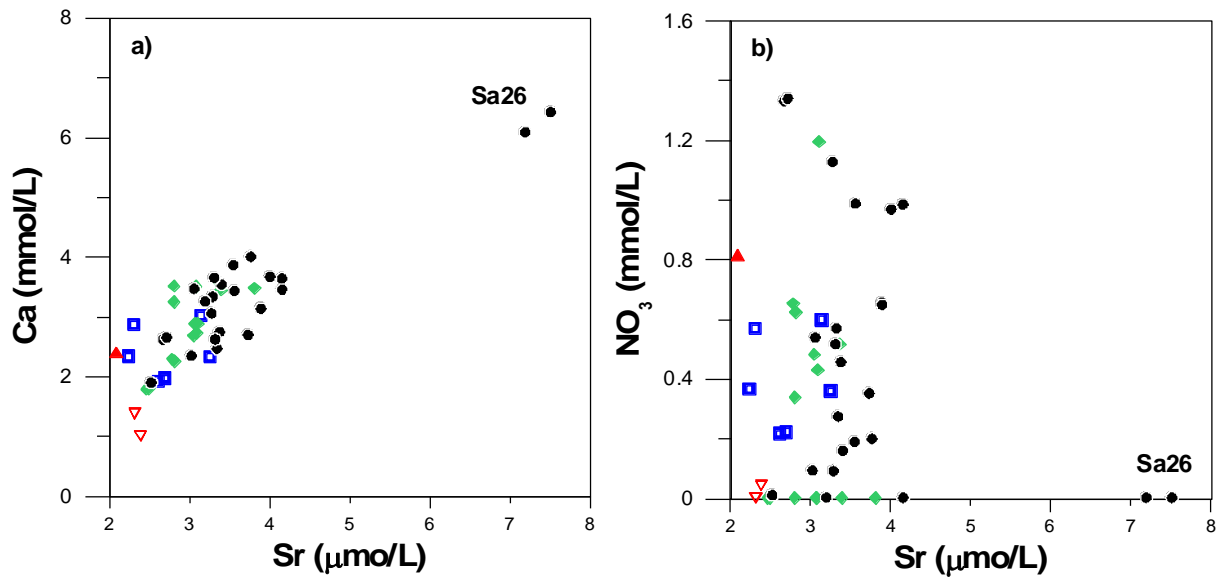


Figure 6 : Ca vs. Sr and NO<sub>3</sub> vs. Sr for surface and groundwater sampled at the La Bassée plain in June and November 2007 and groundwater sampled upstream (Chalk aquifer)

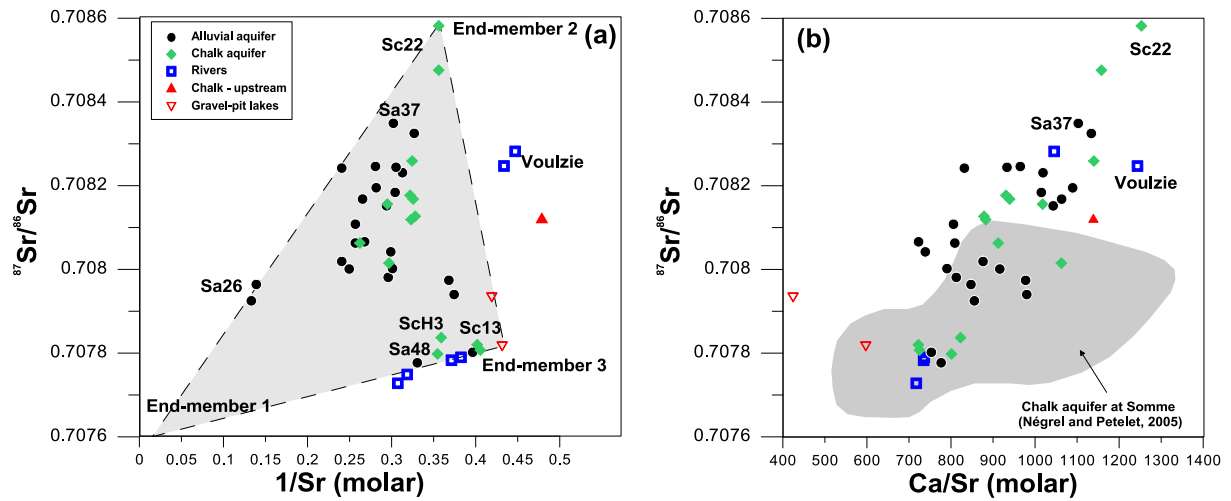


Figure 7 :  $^{87}\text{Sr}/^{86}\text{Sr}$  vs.  $1/\text{Sr}$  (molar) and  $^{87}\text{Sr}/^{86}\text{Sr}$  vs.  $\text{Ca}/\text{Sr}$  (molar) for surface and groundwater sampled at La Bassée plain in June and Novembre 2007 and one upstream well

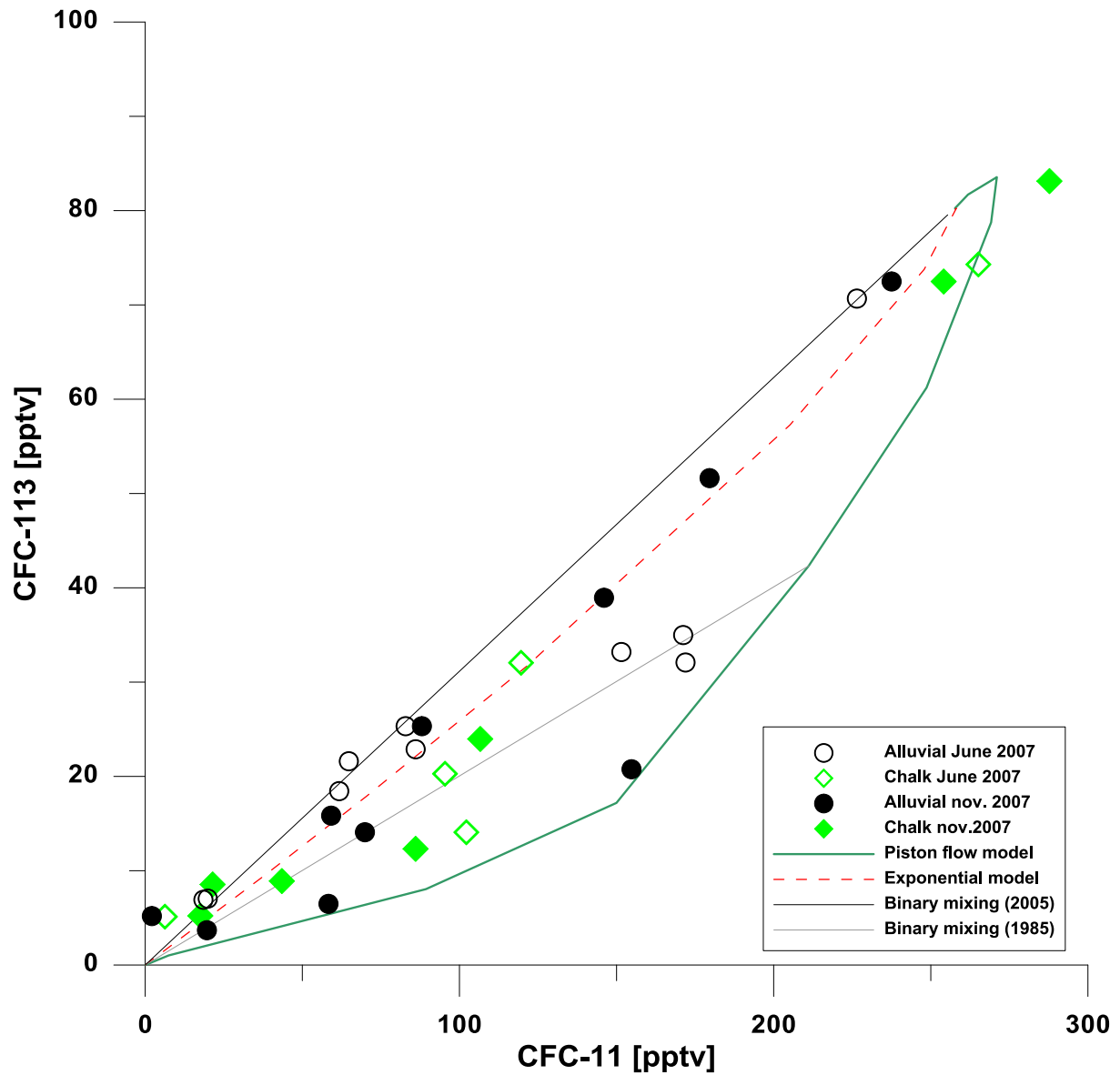


Figure 8 : CFC-11 vs. CFC-113 (in pptv) for groundwater collected in the La Bassée site in June and November 2007 and piston flow, exponential and binary mixing of young water (recharged in 1985 and 2005) with CFC-free water reference lines

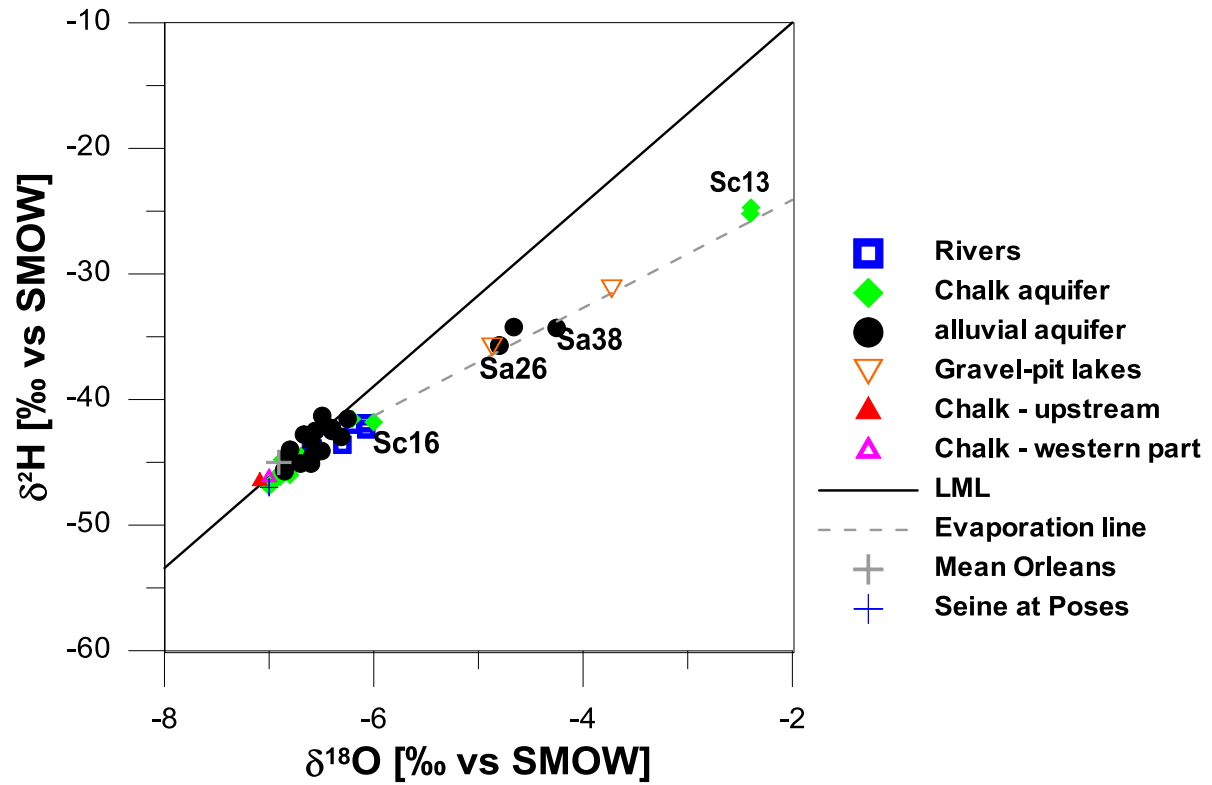


Figure 9 :  $\delta^{2}\text{H}$  vs  $\delta^{18}\text{O}$  for surface and groundwater collected in the La Bassée site in June and November 2007; local meteoric line and mean weighted values for precipitations at Orléans (1996-2010), mean of Seine water at Poses (1974-1976) and calculated evaporation line

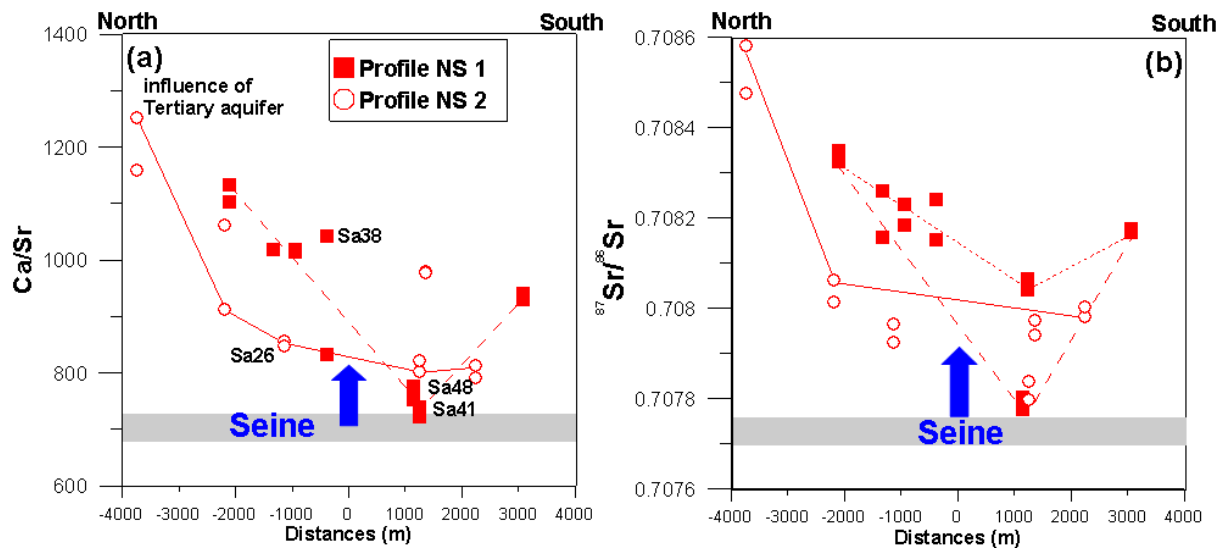


Figure 10:  $^{87}\text{Sr}/^{86}\text{Sr}$  vs. distance and Sr/Ca vs. distance for the groundwater collected in June and November 2007 following the two North-South profiles

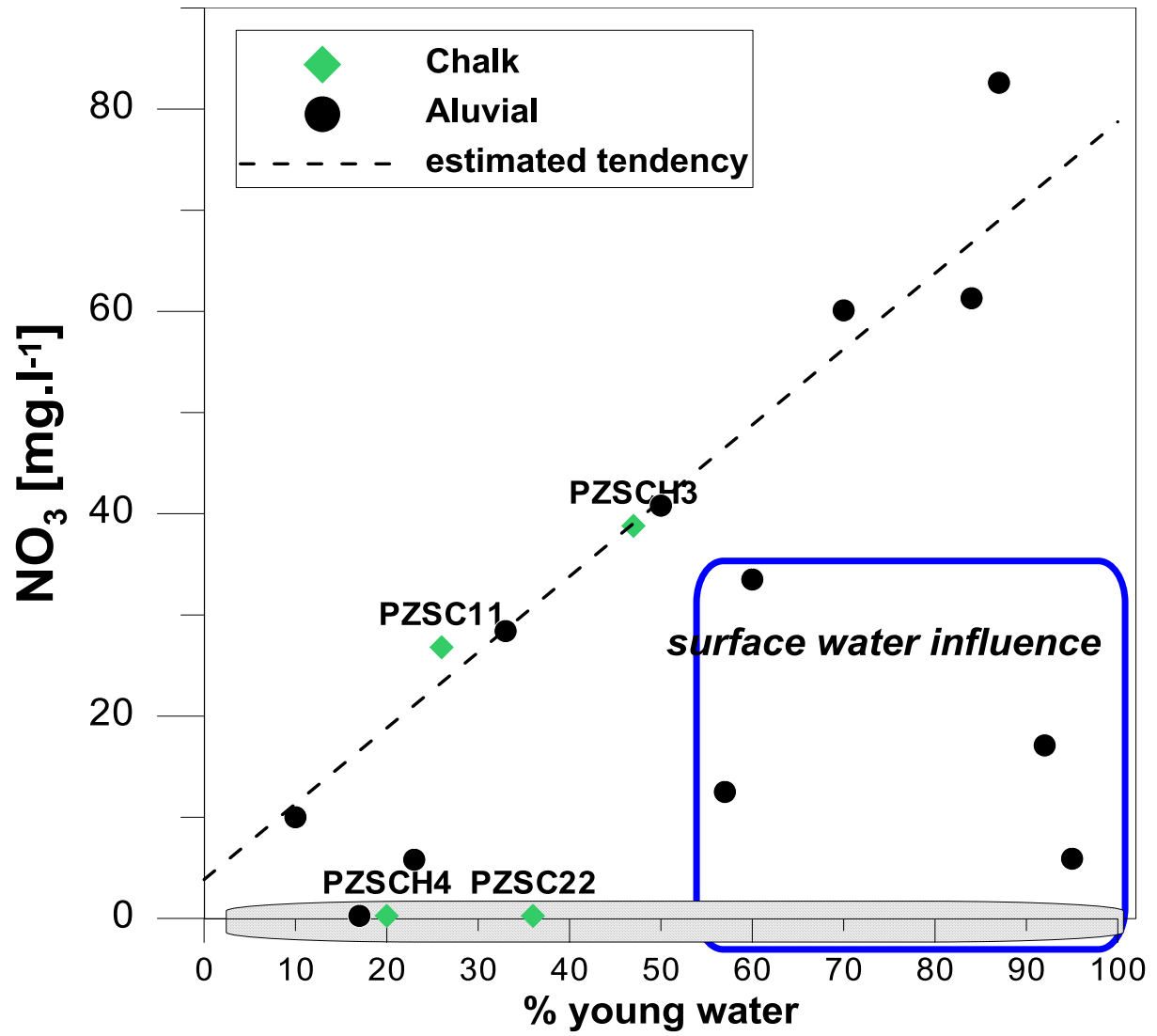


Figure 11:  $\text{NO}_3$  vs. % of young groundwater for groundwater sampled in June and November 2007 in the La Bassée alluvial plain