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# Application of a multidisciplinary and integrative Weight-of-Evidence approach to a one-year monitoring survey of the Seine River

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1 **Abstract**

2 Quality assessment of environments under high anthropogenic pressures such as the Seine Basin,  
3 subjected to complex and chronic inputs, can only be based on combined chemical and biological  
4 analyses. The present study integrates and summarizes a multidisciplinary dataset acquired throughout  
5 a one-year monitoring survey conducted at three workshop-sites along the Seine River (PIREN-Seine  
6 program), upstream and downstream of the Paris conurbation, during four seasonal campaigns, using a  
7 Weight-of-Evidence (WOE) approach. Sediment and water column chemical analyses,  
8 bioaccumulation levels and biomarker responses in caged gammarids, and laboratory (eco)toxicity  
9 bioassays were integrated into four lines of evidence (LOEs). Results from each LOE clearly reflected  
10 an anthropogenic gradient, with contamination levels and biological effects increasing from upstream  
11 to downstream of Paris, in good agreement with the variations in the structure and composition of  
12 bacterial communities from the water column. Based on annual average data, the global hazard was  
13 summarized as ‘moderate’ at the upstream station and as ‘major’ at the two downstream ones.  
14 Seasonal variability was also highlighted; the winter campaign was least impacted. The model was  
15 notably improved using previously established reference and threshold values from national-scale  
16 studies. It undoubtedly represents a powerful practical tool to facilitate the decision-making processes  
17 of environment managers within the framework of an environmental risk assessment strategy.

18

19 *Keywords:* Seine River, Environmental risk, Weight-of-Evidence, Pollutants, Bioavailability,  
20 Biomarkers, Bioassays, Bacterial community

21

## 22 **1. Introduction**

23 The Seine river basin represents a catchment area of around 78,600 km<sup>2</sup> from its source at Seine-  
24 Source near Dijon in north-eastern France to its mouth in the English Channel in the northwestern city  
25 of Le Havre. It is supplied by a fairly regular network of tributaries. The central zone of the watershed  
26 is the convergence area of the main tributaries of the Seine River, and is occupied by the large Paris  
27 conurbation. In total, just over a quarter of the French population (~17.5 million) lives in this  
28 watershed, mostly (85%) in urban areas. The Seine watershed also harbors very intensive agricultural  
29 activities resulting in substantial diffuse sources of nutrients and pollutants such as pesticides (Billen  
30 et al. 2007). The heavy urbanization and industrialization of the Paris area also result in significant  
31 inputs of contaminants into the Seine River basin, including metals and persistent toxic substances  
32 such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) (Blanchard  
33 et al. 2007; Thévenot et al. 2007). The wide variety of anthropogenic pressures that affect the Seine  
34 watershed makes this area an ideal case study of contemporary environmental problems in developed  
35 countries: the river's water quality and ecological status integrate and reflect the complex functioning  
36 of the watershed, especially the ways humans have shaped and exploited land- and water-scapes  
37 (Billen et al. 2007). However, the complexity and diversity of exogenous inputs result in an equally  
38 complex, diffuse, and chronic pressure on the ecosystems of the Seine continuum. The biological  
39 effects and long-term impacts of this pressure on the biota still remain difficult to evaluate directly.

40 The contamination level at a particular site can be quite readily determined through chemical analysis  
41 as defined by the presence of '*substances that would not normally occur or at concentrations above*  
42 *the natural background*'. However, 'pollution status' assessment additionally integrates chemical  
43 bioavailability and the biological impacts of contaminants on the environment (Chapman 2007).  
44 Consequently, it is now widely admitted that an efficient environmental risk assessment (ERA) should  
45 be conducted through an integrated and multidisciplinary strategy to provide answers to all these  
46 concerns. Moreover, such approaches are clearly recommended and even required by the European  
47 Water Framework Directive 2000/60/CE (European Commission (EC) 2000).

48 Between 2011 and 2012, eight research teams collaborated on a synchronous and integrative multi-  
49 marker approach aiming at a global assessment of the chemical and ecological/ecotoxicological status  
50 of three workshop-sites along the Seine axis situated upstream and downstream of Paris (PIREN-Seine  
51 program) (Fig. 1). This one-year monitoring program consisted of four field measurement campaigns  
52 corresponding to distinct seasons. During each sampling period, a wide panel of biological and  
53 chemical analyses was performed to characterize in detail the quality of the aquatic environment at  
54 each sampling location based on six fundamental aspects: (i) the physico-chemical quality of the water  
55 column and sediment, (ii) a comprehensive analysis of metal and organic contaminants in the same  
56 two compartments, (iii) the bioaccumulation of contaminants of concern in field-transplanted

57 gammarids and river biofilms, (iv) the biological responses in these gammarids exposed *in situ*, (v) the  
58 spatio-temporal variations in autochthonous bacterial community composition and metal tolerance  
59 acquisition, and (vi) the (eco)toxicity of water and sediment samples in laboratory bioassays. In total,  
60 about 550 parameters were monitored *per* site and *per* sampling period. Thus, one of the main  
61 challenges was to find a way to summarize and interpret the large dataset issued from this multi-  
62 marker study.

63 To achieve this objective, the concept of Weight of Evidence (WOE) appeared as an adequate strategy  
64 for a global and integrative multidisciplinary assessment of environmental quality in the area, because  
65 it is based on the packaging of a wide variety of data within several lines of evidence (LOEs). In each  
66 LOE the contamination level assessed through chemical analyses is combined with bioavailability  
67 analyses and biological responses from key species and/or model organisms at different levels of  
68 biological organization (Chapman et al. 2002; Dagnino et al. 2008). The resulting environmental  
69 diagnosis is based on the calculation of a hazard index for each LOE, which is then plotted on an  
70 evaluation grid allowing for clear and rapid hazard classification (Chapman et al. 2002; Dagnino et al.  
71 2008; Piva et al. 2011). We also propose a global hazard evaluation that compiles all calculated LOE  
72 indices within a single one that is also finally assigned to a hazard class. This approach was  
73 successfully applied to the assessment of the health status in multi-contaminated environments such as  
74 harbors, urbanized and/or industrial areas (*e.g.*, Piva et al. 2011; Benedetti et al. 2012; Bebianno et al.  
75 2015). These studies generally focused on sediment hazard assessment. However, the WOE approach  
76 is also applicable to other matrices such as effluents, water, and soils (Chapman et al. 2002; Chapman  
77 2007; Dagnino et al. 2008), and to more global environmental diagnosis such as aquatic and terrestrial  
78 hazard assessment (Chapman et al. 2002; Chapman 2007; Piva et al. 2011).

79 Relying on the above-mentioned promising applications of the WOE procedure to sediment hazard  
80 assessment, the present study implements this multicriteria-based environmental diagnosis to a one-  
81 year monitoring survey of the Seine River axis. The three model sites investigated in the present work  
82 are situated along the Seine River continuum and characterized by a strong contamination gradient  
83 from upstream to downstream of the Paris urban area (Priadi et al. 2011; Fechner et al. 2012; Teil et al.  
84 2014). As the WOE model described by Piva et al. (2011) relies on the calculation of Ratio-to-  
85 Reference (RTR) values, only part of the data obtained during the 2011-2012 campaigns was selected.  
86 The upstream station is often considered as a 'reference' site in similar case studies. This station was  
87 expected to be relatively unaffected by direct inputs from the Paris conurbation, but it was probably  
88 impacted by the intense agricultural activities surrounding the densely urbanized area, as well as by  
89 domestic or industrial inputs from the relatively small cities located upstream. The use of 'external  
90 reference' values established from several field-monitoring campaigns and physiological studies on  
91 the selected sentinel organisms would make it possible to classify all sites, including the upstream one.  
92 To that purpose, biomarkers and bioaccumulation levels were analyzed through an active approach in

93 transplanted *Gammarus fossarum* crustaceans, a common species in the field of ecotoxicology and  
94 biomonitoring. Gammarids have been reported as efficient accumulators of organic compounds and  
95 metals, whether essential or not (Besse et al. 2013; Lebrun et al. 2014). Besides, they are commonly  
96 used for the development of exposure biomarkers because they are easily sampled in the field and  
97 handled (Besse et al. 2013; Dedourge-Geffard et al. 2013; Lebrun et al. 2014). Moreover, translocated  
98 gammarid populations have been fully characterized, and reference levels are (or could be) established  
99 for bioaccumulation levels and biomarker responses (Xuereb et al. 2009; Geffard et al. 2010; Coulaud  
100 et al. 2011; Besse et al. 2013; Charron et al. 2013). According to the existence of reference levels or  
101 the possibility to derive them for each endpoint, the dataset selected for WOE integration was the  
102 following:

103 (1) Chemical hazard (LOE#1) was characterized through pesticide (PEST), alkylphenol (AKP), metal  
104 element (ME), and perfluoroalkyl substance (PFAS) analysis in the water column. MEs and PFASs  
105 were also measured in composite sediment samples together with more hydrophobic and (very)  
106 persistent compounds such as PAHs, PCBs, polybromodiphenyl ethers (PBDEs), and organochlorine  
107 pesticides (OCPs);

108 (2) Bioavailability (LOE#2) of the chemicals of concern, including PAHs, PCBs, PBDEs, OCPs, and  
109 MEs, was assessed by measuring bioaccumulation levels in caged gammarids;

110 (3) Biological responses (LOE#3) in the same population of transplanted gammarids were assessed  
111 using validated biomarkers such as digestive enzyme activity, feeding rate, reproductive toxicity, and  
112 acetylcholinesterase (AChE) activity;

113 (4) (Eco)toxicological responses at the organism/cellular level were also investigated using laboratory  
114 bioassays (LOE#4) performed on water column and sediment samples. They included genotoxicity,  
115 cytotoxicity, and endocrine disruption (ED) *in vitro* bioassays, as well as a fish embryo toxicity test,  
116 the Medaka embryo-larval assay (MELA).

117 The overall aim of this study was to confirm the importance and relevance of a multidisciplinary  
118 survey of aquatic environment quality. Such an approach is not realistically applicable in an ERA  
119 strategy without a practical tool to integrate and fruitfully interpret the resulting large dataset within a  
120 global environmental context. The present work applies the WOE model, adapted from Piva et al.  
121 (2011), to a practical case study on the Seine River continuum. The aim of this integrative approach is  
122 to assess the overall quality of the aquatic environment and prioritize hazards at each of the three sites.  
123 Such an approach could represent a promising decision-making tool for environmental managers.

124

125

## 126 **2. Materials and Methods**

### 127 *2.1. Studied area and sampling procedure*

128 The three sampling sites were previously described by Lebrun et al. (2015) and Faburé et al. (2015).  
129 Briefly, these sites are situated along the Seine River in the north of France (Fig. 1). Marnay  
130 (48°31'35.8" N, 3°33'29.6" E) is located approximately 200 km upstream of Paris, in a non-  
131 urbanized area, and therefore expected to be at least partially free from direct inputs from the Paris  
132 conurbation. Conversely, Bougival (48°52'11.2" N, 2°07'47.1" E) and Triel (48°58'55.5" N,  
133 1°59'53.1" E) are both situated downstream of Paris and its conurbation, at respective distances of  
134 approximately 40 and 80 km (Fig. 1). These stations are affected by various contamination inputs in  
135 relation to intense anthropogenic activities (Priadi et al. 2011, Teil et al. 2014). Sampling was  
136 performed at these sites during four campaigns undertaken in fall (C1 campaign, from August 31<sup>st</sup> to  
137 September 27<sup>th</sup>, 2011), spring (C2 campaign, from March 2<sup>nd</sup> to April 3<sup>rd</sup>, 2012), summer (C3  
138 campaign, from June 1<sup>st</sup> to July 3<sup>rd</sup>, 2012), and winter (C4 campaign, from November 13<sup>th</sup> to  
139 December 18<sup>th</sup>, 2012), corresponding to contrasted temperature and flow rate conditions.

140 Dissolved metal concentrations were determined at the three sites during each sampling period (Faburé  
141 et al. 2015; Lebrun et al. 2015). At the end of each seasonal campaign, water was collected at each  
142 station as follows: 1 L of raw water in amber glass bottles for endocrine disruption bioassays, 10 L of  
143 raw water in high-density polyethylene (HDPE) containers for MELA, 20 L of raw water in two 10-L-  
144 HDPE containers for microbial community analyses. All containers were rinsed three times with river  
145 water before being filled in the field; they were all brought back to the laboratory in a cool box and  
146 then kept at 4 °C until further use. In addition, two 250-mL-HDPE bottles were filled in a similar way  
147 and stored at -20 °C for organic contaminant analyses. Prior to analyses, samples were thawed and  
148 filtered through GF/F (0.7 µm) Whatman glass microfiber filters previously ignited at 450°C for 6 h.

149 For each campaign (except C3), one composite surface (0–2 cm) bed sediment sample was collected in  
150 an aluminum container, brought back to the laboratory in a cool box, and stored either at 4 °C for  
151 bioassays or at -20 °C until freeze-drying, grinding and 2 mm-sieving for chemical analyses.

152

### 153 *2.2. Field-caged gammarid exposure*

154 The procedures are detailed in previous studies (Coulaud et al. 2011; Besse et al. 2013; Lebrun et al.  
155 2015). Briefly, gammarids (*Gammarus fossarum*) were collected by kick sampling at La Tour du Pin,  
156 upstream of the Bourbre River (France). This site displays good water quality according to the data  
157 records of the RNB (French Watershed Biomonitoring Network). After a 15-day acclimatization



158 period in the laboratory (conditions detailed in Besse et al. (2013)) and 24 hours before *in situ* caging,  
159 8 groups of 20 adult gammarids (10-11 mm) were caged in polypropylene cylinders (10 cm length, 5.5  
160 cm diameter) capped at the ends with pieces of net (1 mm mesh) to ensure free water circulation. To  
161 assess the effects on reproduction, three supplemental experimental systems, each containing seven  
162 precopulatory pairs with D2-molt stage females (*i.e.*, hatched juveniles in brood pouches and visible  
163 oocytes) were set up. A temperature probe was placed in the water to record temperature every hour  
164 throughout the experiment. During the tests, gammarids were fed with the same alder (*Alnus*  
165 *glutinosa*) leaves as during the acclimatization period in the laboratory, pre-conditioned for at least  
166  $6 \pm 1$  days in groundwater.

167 After 7 days of exposure, two replicates were collected and brought to the laboratory for  
168 bioaccumulation measurements in whole organisms (3 pools of 5 gammarids) for each site. After 15  
169 days of exposure, three replicates *per* site were collected and brought to the laboratory. Gammarids  
170 from the same site were collected, counted (for survival rate assessment), then male gammarids were  
171 pooled, dried, weighed, flash frozen in liquid nitrogen and stored at  $-80$  °C until digestive enzyme  
172 activity and AChE activity were analyzed. Leaf consumption was used to estimate the feeding rate for  
173 each site and campaign. After 30 days of exposure, the last three replicates were collected and brought  
174 to the laboratory. Gammarids from the same site were pooled together and counted (for survival rate  
175 assessment); females were then selected to analyze reproduction markers (molt delay, number of  
176 embryos/oocytes *per* female).

177

## 178 2.3. Chemical analyses

### 179 2.3.1. Metal element measurements

180 For metal determination in caged gammarids, 3 pools of 5 individuals were digested by HNO<sub>3</sub> and  
181 H<sub>2</sub>O<sub>2</sub>, as detailed by Lebrun et al. (2015). A reference material (Mussel Tissue ERM-CE278, LGC  
182 Promochem, Molsheim, France) was included in each digestion series to control the quality of  
183 digestion.

184 About 0.1 g of sediment was mineralized in closed Teflon vessels under a hood using a heating block  
185 (Digiprep, SCP Science). A three-step digestion was performed as described by Priadi et al. (2011). A  
186 geostandard was included in each digestion series (IAEA lake sediment SL1) to control chemical  
187 mineralization efficiency. All reagents used for the digestion processes were ultrapure reagents to  
188 avoid contamination.

189 Major and minor element concentrations were determined in filtered acidified water and in digested  
190 sediment and gammarid solutions by inductively coupled plasma quadrupolar mass spectrometry

191 (ICP-QMS; X-Series, CCT II+ Thermoelectron, France), as previously described (Faburé et al. 2015;  
192 Lebrun et al. 2015, Le Pape et al. 2012, Priadi et al. 2011). Accuracy checking (SRM 1640a, NIST,  
193 Gaithersburg, USA) and plasma fluctuation corrections were also performed as described in the same  
194 references.

195

### 196 2.3.2. Organic compound analysis

197 Organic micropollutants were determined using previously established methods. Briefly, dissolved  
198 (<0.7 µm fraction) pesticides and PFASs were extracted using solid phase extraction with polymeric  
199 sorbents (100-500 mL samples) followed by analysis by liquid chromatography coupled to tandem  
200 mass spectrometry (Dufour et al. 2015; Munoz et al. 2015), while alkylphenols were determined using  
201 solid-phase microextraction (SPME) and gas chromatography coupled to mass spectrometry (Belles et  
202 al. 2014). Freeze-dried sediment (1 g) or gammarid (0.2 g) samples were extracted using microwave-  
203 assisted extraction followed by solid phase extraction adsorption chromatography clean-up (Budzinski  
204 et al. 2000; Noura et al. 2013; Munoz et al. 2015).

205

## 206 2.4. Biomarker analysis

### 207 2.4.1. Digestive enzyme activity

208 The enzymatic activity of two carbohydrases (amylase and cellulase) and a protease (trypsin) was  
209 determined as previously described by Charron et al. (2013), using starch (1%), carboxymethyl-  
210 cellulose (2%), and N-benzoyl-DL-arginine 4-nitroanilide hydrochloride (3 mM) as substrates,  
211 respectively.

212

### 213 2.4.2. AChE activity

214 AChE activity was analyzed as described in Xuereb et al. (2009) according to the colorimetric method  
215 initially developed by Ellman et al. (1961), with DTNB (5,5'-dithiobis(2-nitrobenzoic acid) as a  
216 substrate.

217

### 218 2.4.3. Feeding rate assessment

219 Feeding rates were calculated according to the method described by Coulaud et al. (2011).  
220 Calculations were based on leaf disc scanning and expressed as consumed surface *per day per* living  
221 gammarid ( $\text{mm}^2 \text{d}^{-1} \text{organism}^{-1}$ ).

222

#### 223 2.4.4. Reproduction markers

224 At the end of the exposure period (30 days), the size, molting stage, number of oocytes and embryos  
225 *per* female were determined according to Geffard et al. (2010). To accurately assess the females' molt  
226 stages, the third and fourth peripod pairs (dactilopodite and protopodite) of females were cut off,  
227 mounted on a microscope slide with a coverslip, and their integumental morphogenesis was observed  
228 ( $\times 200$ ) to discriminate among the five molt stages (AB, C1, C2, D1, and D2). The number of oocytes  
229 *per* female in C2/D1-molt stage was determined by *in vivo* observation of the two ovaries under a  
230 binocular microscope. In the same way, embryos of females bearing a brood in 2<sup>nd</sup>, 3<sup>rd</sup>, or 4<sup>th</sup>  
231 embryonic stage were manually recovered from the marsupium, placed on a slide with water, and  
232 counted under a binocular microscope. Desynchronization between female molt stage and embryonic  
233 development stage was also recorded to assess delays in female molt cycle (Geffard et al. 2010).

234

### 235 2.5. Bioassays

#### 236 2.5.1. Endocrine disruption *in vitro* bioassays

237 Endocrine disruption (ED) bioassays were conducted on organic extracts prepared in  
238 dimethylsulfoxide (DMSO) from water column samples (1 L) or from freeze-dried sediment samples  
239 (1 g) according to Jagan et al. (2009) and Kinani et al. (2010), respectively. Three luciferase reporter  
240 bioassays were used to evaluate the ED potential of organic extracts from sediment or water column:  
241 using MELN cells (Balaguer et al. 1999), PC-DR-LUC cells (Jagan et al. 2007), or MDA-kb2 cells  
242 (Wilson et al. 2002), we measured disruptions of the transcriptional activity of the estrogen receptor  
243  $\text{ER}\alpha$  (ER), of the thyroid receptor  $\text{TR}\alpha 1$  (TR), and of the androgen (AR) and glucocorticoid (GR)  
244 receptors, respectively, by bioluminescence.

245 The results were expressed as fold induction in relative luminescence units (RLUs) as compared to  
246 luciferase activity of the solvent control (DMSO 0.1%). Only RLU values significantly different from  
247 that of the solvent control (Student's *t*-test,  $p < 0.05$ ) were considered as above the LD. Any detectable  
248 RLU levels above the bottom value of the sigmoidal dose-response curves of reference ligands were  
249 considered as above the LQ. This threshold value of the sigmoid was obtained by nonlinear regression  
250 of the Hill equation (GraphPad Prism 5 Software, San Diego, CA, USA). Furthermore, only RLU

251 levels significantly different from that of the corresponding blank value (Student's *t*-test,  $p < 0.05$ )  
252 were taken into account.

253

#### 254 2.5.2. Microtox<sup>®</sup> and SOS Chromotest procedures

255 The two bioassays were performed on sediment elutriates to measure the toxicity of water-extractable  
256 pollutants. After thawing overnight at 4 °C, 6 g wet weight of sediment were mixed with 24 mL of  
257 deionized water for 10 min at 300 rpm. The solid phase was pelleted at 1,800 × g for 10 min, and the  
258 supernatant was immediately collected and stored at 4 °C in the dark prior to toxicity testing within  
259 24 h.

260 For the Microtox<sup>®</sup> assay, the standard procedure of the Acute Toxicity Basic Test was used (AZUR  
261 Environmental 1998; ISO 1999). Bioluminescence was measured after 30 min on duplicated series of  
262 elutriate serial dilutions using a Microtox Model 500 analyzer (Azur Environmental).

263 The SOS-Chromotest developed by Quillardet and Hofnung (1985) was miniaturized in microplates.  
264 Briefly, *E. coli* PQ37 strain was exposed to the elutriate (3% final, v/v) for 3 h at 37 °C, in triplicate,  
265 with and without the liver S9 fraction (10% final, v/v) from β-naphthoflavone- and phenobarbital-  
266 treated rats (Trinova-Biochem). Following exposure, beta galactosidase (BG) and alkaline phosphatase  
267 (AP) activity levels were measured colorimetrically at 420 nm (Fluo Star Optima, BMG Labtech). The  
268 SOS control-relative induction factor (IF) was calculated by dividing the BG/AP activity ratio of the  
269 sample by the solvent control BG/AP ratio, as described by Quillardet and Hofnung (1985). Results  
270 were expressed as mean induction factor ± standard deviation (three replicates).

271

#### 272 2.5.3. Medaka embryo-larval assay (MELA)

273 Japanese Medaka (*Oryzias latipes*) embryos of the CAB strain were provided by the UMS Amagen (Gif-  
274 sur-Yvette, France) 1 day post fertilization (dpf).

275 Whole sediment toxicity was evaluated by the Medaka Embryo-Larval Assay in sediment contact  
276 (MELAc), using the protocol described by Barhoumi et al. (2016). Reference non-contaminated  
277 sediment (Yville-sur-Seine) was used as a negative control (Vicquelin et al. 2011). Briefly, 25 embryos  
278 *per* replicate were laid onto a Nitex<sup>®</sup> mesh at the sediment surface and immersed into egg-rearing  
279 solution (ERS). To avoid hypoxia at the sediment-water interface, ERS was thoroughly renewed and  
280 dissolved oxygen was measured daily.

281 The toxicity of water samples was evaluated by the Medaka Embryo-Larval Assay in 96-well  
282 microplates, adapted from Helmstetter and Alden (1995). Before testing, the water samples were filtered  
283 through 0.8 µm-filters (Millipore) to remove particles. Twenty-five embryos *per* condition were  
284 individually incubated in 300 µL of water sample. Water was renewed daily, and spring water  
285 (Cristaline) was used as a negative control.

286 The procedure was similar for the two assays, and followed previously published protocols (Vicquelin  
287 et al. 2011; Barjhoux et al. 2012; Barhoumi et al. 2016). In summary, exposure was performed at  
288  $26 \pm 0.3$  °C, and stopped at the first hatching peak in one of the test conditions (10-11 dpf). Hatchlings  
289 and unhatched embryos were transferred to clean water or ERS, respectively, for three additional days.  
290 Viability, time to hatch, hatching success, body and head length, and developmental abnormalities  
291 were recorded in embryos and larvae according to Barjhoux et al. (2012).

292

## 293 *2.6. Bacterial community composition*

294 An aliquot (from 0.8 L to 5.0 L) of each water sample was filtered through a 0.2 µm pore-size, 47-  
295 mm-diameter polycarbonate filter (Millipore, MA). All filters were stored at -20 °C until use. DNA  
296 was extracted using phenol-chloroform-isoamyl alcohol, following an enzymatic cell lysis stage in  
297 the presence of lysozyme, mutanolysine and sodium dodecyl sulfate. Bacterial community structure  
298 (number and relative abundance of the different taxa) was assessed by pyrosequencing of the V1-V3  
299 region of the bacterial 16S rRNA gene, and downstream sequence analysis was performed using the  
300 software program MOTHUR (full procedure described in García-Armisen et al. 2014).

301 Using the PRIMER v6 software program, we compared bacterial community structures among  
302 samples based on Bray-Curtis coefficient matrix, after square-root transformation of the data. This  
303 coefficient evaluates the dissimilarity between each pair of samples in terms of species abundance.  
304 The resulting matrix was used as a basis for a graphic representation of dissimilarities in a non-metric  
305 multi-dimensional scaling (NMDS) graph, where each sample was represented by a dot; the more  
306 different the structures of two bacterial communities, the further apart the two corresponding dots on  
307 the graph.

308

## 309 *2.7. Data integration within the Weight-of-evidence (WOE) approach*

310 The data selected to characterize contamination levels (*i.e.*, chemical analyses) in the area,  
311 contaminant bioavailability (*i.e.*, bioaccumulation levels in caged gammarids), and *in situ* biological  
312 responses (*i.e.*, biomarkers in gammarids) and following laboratory exposure (*i.e.*, bioassays) were

313 integrated into a WOE approach according to Piva et al. (2011). Slight modifications and/or  
314 adaptations were made and are described below.

315

#### 316 2.7.1. Line of evidence 1: sediment and water column chemistry (LOE#1)

317 Among the 210 metal and organic compounds analyzed in the abiotic compartment, we selected  
318 chemicals to be included in the WOE approach according to their mention in reference studies  
319 (MacDonald et al. 2000; Piva et al. 2011), and French and European regulatory documents (EC 2000,  
320 2013; French Ministry of Ecology Energy Sustainable Development and Planning (MEDAD) 2007,  
321 2015). The reference values used in LOE#1 calculations were environmental quality standards (EQSs)  
322 or environmental guideline values (EGVs) of the Ineris (French National Institute for Environmental  
323 Technology and Hazards) when available. Otherwise, Predicted No Effect Concentrations (PNECs)  
324 were gathered from environmental institutes recognized at the European level (Environment Agency,  
325 Ineris, Anses, and European Chemical Agency) and key reports (MacDonald et al. 2000; European  
326 Union (EU) 2005; MEDAD 2006; Dulio and Andres 2014). Then, the geometric mean of the PNECs  
327 was used as the reference value. Details on the selected reference values and the list of chemicals are  
328 given in Table S1 (for the water column) and Table S2 (for the sediment) in the Electronic  
329 Supplementary Material (ESM). Note that for both metal and organic compound analysis, data below  
330 the limit of detection (LD) were set at LD/2 before being integrated into calculations. Moreover, when  
331 the reference value was lower than the corresponding LD/2, measured concentrations below the LD  
332 were removed from the dataset.

333 The detailed calculation procedure implemented in LOE#1 is presented in ESM Fig. S1. As described  
334 by Piva et al. (2011), the elaboration of the chemical data into the corresponding hazard quotient (HQ)  
335 was based on the calculation of a ratio-to-reference (RTR) for each chemical and its weighting ( $RTR_w$ )  
336 according to chemical status within the Water Framework Directive (WFD) 2013/39/EU (EC 2013)  
337 (see ESM Tables S1 and S2).

338 The global Chemical Hazard Quotient (ChemHQ) was calculated by averaging the  $RTR_w$  values for  
339 chemicals whose measured concentrations were below or equal to the reference level (*i.e.*,  $RTR \leq 1$ )  
340 and summing the  $RTR_w$  values for chemicals whose concentrations exceeded the reference (*i.e.*,  
341  $RTR > 1$ ). With this calculation procedure, the resulting ChemHQ value increases with the number  
342 and the magnitude of exceeding endpoints, but is not strongly influenced by the number of chemicals  
343 whose concentrations are below the respective reference levels (Piva et al. 2011). This quotient was  
344 calculated for each site and each campaign, for the water column ( $ChemHQ_{water}$ ) and the sediment  
345 ( $ChemHQ_{sed}$ ). A hazard class was finally assigned to each calculated ChemHQ value according to the  
346 hazard classification grid established by Piva et al. (2011).

347 The contribution of each chemical and class of substance to the ChemHQ value was also calculated.

348

### 349 2.7.2. Line of evidence 2: bioavailability (LOE#2)

350 Bioavailability was assessed through bioaccumulation measurements in whole gammarids.

351 Concentrations measured in gammarids following the caging procedure with control food supply have  
352 to be regarded as mainly proceeding from the water column rather than from the trophic route. Besse  
353 et al. (2013) used the same experimental conditions to study the bioaccumulation levels of 11 MEs and  
354 38 hydrophobic organic compounds (including PAHs, PCBs, PBDEs, and OCPs) in gammarids *G.*  
355 *fossarum* of the same geographical origin as those used in the present study. In particular, the authors  
356 established bioaccumulation thresholds for 35 substances permitting to reveal bioavailable  
357 contamination of the environment when values go beyond these reference levels. These threshold  
358 tissue concentrations were used to derive the reference levels for bioaccumulation data in the present  
359 study. The list of the selected chemicals for LOE#2 and their respective reference values are presented  
360 in ESM Table S3.

361 Based on the procedure of Piva et al. (2011), the calculation method applied to LOE#2 was quite  
362 similar to LOE#1, with the calculation of an RTR value for each chemical and the weighting of these  
363 values according to the status of that chemical within the WFD (see Section 2.7.1). One of the  
364 differences between the two LOEs is related to the addition of a correction function ( $Z(i)$ ) to take into  
365 account the significance of the deviations from the reference values (Piva et al. 2011). As three  
366 replicates were not available for every compound and reference value, we set the correction function  
367  $Z(i)$  as a fixed factor, as proposed by the authors. A hazard class was attributed to each resulting  $RTR_w$   
368 value, as described by the authors.

369 The Bioavailability Hazard Quotient (BioavHQ) for each site and each campaign was calculated by  
370 averaging the  $RTR_w$  values whose relative hazard was classified as 'slight' and summing the  $RTR_w$   
371 values with a 'moderate' to 'severe' hazard class, following the same reasoning as applied in LOE#1  
372 (see Section 2.7.1). A global hazard class for bioavailability was attributed to each BioavHQ, as  
373 described by Piva et al. (2011). As in the case of LOE#1, the contribution of each chemical and class  
374 of substance to the BioavHQ value was calculated. Details on the complete calculation procedure  
375 implemented in LOE#2 are presented in ESM Fig. S2.

376

### 377 2.7.3. Line of evidence 3: biomarkers (LOE#3)

378 The calculation method described by Piva et al. (2011) for biomarker LOE required a reference value  
379 (or control value) and an effect (inhibition and/or induction) threshold for each biomarker.

380 Only unilateral differences in comparison to reference values were taken into account, in agreement  
381 with their biological significance. As a result, only inhibition responses were taken into account for  
382 AChE activity, feeding rate, digestive enzyme activity levels, and the number of oocytes and embryos  
383 *per* female. In contrast, only induction effects were taken into account for mortality and molt delay  
384 endpoints. However, bilateral differences could be taken into account in the case of biomarkers for  
385 which both induction and inhibition responses have an (eco)toxicological/biological significance, as in  
386 LOE#4 for the time to hatch of embryos during the MELA (see Section 2.7.4).

387 The calculations of reference and threshold values for gammarid **AChE activities and feeding rates**  
388 were adapted from Xuereb et al. (2009) and Coulaud et al. (2011). They were based on gammarid  
389 weight for AChE activity, and on the size of encaged gammarids and the mean temperature during *in*  
390 *situ* exposure for feeding rates. The thresholds (Th) were calculated according to the unilateral lower  
391 limit of the 95% confidence interval (CI95%) of the corresponding reference value (A. Chaumot,  
392 *personal communication*):

$$393 \quad Th (\%) = \frac{Ref. value - CI95\%lower limit}{Ref. value} \times 100$$

394 For **digestive enzyme activity levels**, mean reference values were taken from Charron et al. (2013).  
395 The corresponding thresholds were calculated as described above for AChE activity levels and feeding  
396 rates.

397 The reference value for the **number of oocytes/embryos *per* female** after normalization of female  
398 size was adapted from Geffard et al. (2010). The corresponding thresholds were calculated as  
399 described above.

400 For the percentage of females with a **molt delay**, we expected the reference value to be 0%, and  
401 calculated the threshold value as the percentage representing the presence of 2 asynchronous females  
402 within a batch of 15 females *per* site and *per* campaign (*i.e.*, 13.3%). As a value equal to '0' is not  
403 acceptable in the calculations of Biomarkers Hazard Quotient (BiomHQ; see details for calculations  
404 below), '100' was added to the reference value (thus equal to 100%) and each measured molt delay  
405 (the threshold remained unchanged).

406 The reference value, threshold, and effect retained for each biomarker are reported in ESM Table S4.  
407 The complete calculation procedure was adapted from Piva et al. (2011), with a few modifications,  
408 and is described in ESM Fig. S3.

409 Briefly, for each biomarker response, we calculated the percentage of variation relatively to the  
410 reference (%VAR). The %VAR is then supposed to be corrected according to the statistical



411 significance of the difference between the reference value and the mean biomarker value ( $Z(i)$ )  
412 function; Piva et al. 2011), resulting in an effect value ( $E(i)$ ) for each endpoint. However, as the  
413 threshold values ( $Th$ ) were pre-established using a statistical approach (*vs.* evaluated by ‘expert  
414 judgement’ in Piva et al. (2011)), we manually set the  $Z(i)$  function, as we did for bioavailability data  
415 (ESM Fig. S3). As mentioned above, only unilateral differences were taken into account. In other  
416 words, when only inhibition was considered as ‘ecotoxicologically relevant’ for a given biomarker,  
417 any induction effect was considered as ‘within the reference range’, resulting in an effect  $E(i)$  set at  
418 ‘0’, and *vice versa*. Moreover, to take into account the fact that the reference value of some biomarkers  
419 could vary depending on exposure conditions over the year, it appeared more accurate to evaluate the  
420 annual average response of a biomarker by averaging the  $E(i)$  values calculated for each campaign  
421 (*per station*) rather than averaging the biomarker responses directly.

422 A hazard class was attributed to each  $E(i)$  value (ESM Table S5) according to the gradation scale of  
423 Piva et al. (2011) (ESM Fig. S3). The effect value was then weighted ( $E_w(i)$ ) against the biological  
424 significance of the biomarker response (ESM Table S6). The Biomarker Hazard Quotient (BiomHQ)  
425 for each site and each campaign was calculated by averaging the  $E_w(i)$  values for which  $E(i)$  relative  
426 hazard was classified as ‘moderate’, and summing the  $E_w(i)$  values for which  $E(i)$  belonged to a  
427 ‘major’ to ‘severe’ hazard class (ESM Fig. S3). The procedure was based on the reasoning applied in  
428 LOE#1 (see Section 2.7.1) and LOE#2.

429 Finally, a global hazard class for biomarkers was attributed to the BiomHQ value for each site and  
430 campaign, as proposed by Piva et al. (2011).

431

#### 432 2.7.4. Line of evidence 4: bioassays (LOE#4)

433 The calculation method applied to derive the Bioassay Hazard Quotient (ToxHQ) was quite similar to  
434 the one used for BiomHQ (Piva et al. 2011), and is described in ESM Fig. S4.

435 The reference values used in the present study were the measurements from the negative control  
436 treatment of each bioassay. Responses from *in vitro* bioassays are usually expressed as induction or  
437 inhibition factors in comparison to the control. Thus, these data were just slightly modified to  
438 correspond to the percentage of variation relatively to the control value (%VAR( $i$ )) defined in ESM  
439 Fig. S4. Afterwards the effect  $E(i)$  was calculated for each endpoint as described for biomarkers, using  
440 threshold ( $Th$ ) values and a correction factor  $Z(i)$  (ESM Fig. S4).

441 For **MELA** results,  $Th$  values were calculated by examining the variability of the data from the  
442 negative control treatment and the associated CI95%, as described above for biomarkers such as AChE

443 activity (see Section 2.7.3). The Z(i) function was consequently set similarly to BiomHQ calculations  
444 (see Section 2.7.3).

445 For *in vitro* bioassays, the Th values were established based on expert judgement. For **Microtox**<sup>®</sup>  
446 results, we set the threshold and the Z(i) function according to acute toxicity levels based on the  
447 inhibition percentage (= % VAR(i)) of the bioluminescence recorded at the highest concentration.  
448 Thus, the Th value set at 10% represented the ‘not toxic’/‘moderately toxic’ limit, according to our  
449 laboratory expertise and adapted from Bennett and Cabbage (1992) and Brouwer et al. (1990). As a  
450 result, data below this value were weighted by a Z(i) factor equal to 0.2 in the effect E(i) calculation.  
451 Similarly, bioluminescence inhibition factors above 10% and below 50% resulted in a weighting Z(i)  
452 value equal to 0.5. When the % VAR(i) was above 50% (*i.e.*, considered as ‘clearly cytotoxic’), the  
453 Z(i) function was equal to 1.

454 A similar methodology was implemented for **SOS Chromotest** data using the threshold value  
455 established by Mersch-Sundermann et al. (1992). As a result, the Th value was set at 50%, in  
456 agreement with the induction factor threshold of 1.5 established as the ‘not genotoxic’/‘marginally  
457 genotoxic’ limit by the authors. Moreover, the Z(i) function was set at (i) 0.2 for a non-significant  
458 value in comparison to the blank and/or for an induction factor below 1.5, (ii) 0.5 for an induction  
459 factor above 1.5 but strictly below 2, and (iii) 1 for an induction factor equal or superior to 2 (value  
460 above which effects could be considered as clearly ‘genotoxic’ according to Mersch-Sundermann et al.  
461 (1992)).

462 For **ED bioassays**, Th values of 50% and 10% were set for agonist (ER, TR, AR/GR) and antagonist  
463 (anti-AR) activities, respectively, according to our laboratory expertise (Lucie Oziol, *personal*  
464 *communication*). The Z(i) function was also manually set at (i) 0.2 for data below the LD or LQ  
465 values, (ii) 0.5 for data not significantly different from the blank value (according to Student *t*-test  
466 results with a 5% risk), (iii) 1 in all other cases.

467 Similarly to the reasoning applied in LOE#3 calculations, only unilateral differences in comparison to  
468 the reference value were taken into account, in agreement with the biological significance of each  
469 endpoint. Thus, any response with an effect other than the one defined as ‘ecotoxicologically relevant’  
470 led to an effect E(i) set at 0, except for the time to hatch of medaka embryos for which bilateral  
471 differences were taken into account.

472 The reference value, threshold, and effect of each endpoint are reported in ESM Table S7. As in the  
473 case of biomarkers, the annual average response of a bioassay endpoint was obtained by averaging the  
474 E(i) values calculated for each campaign at each station. Each effect value E(i) was then weighted  
475 ( $E_w(i)$ ) according to the corresponding bioassay endpoint. The weight of each response was defined as  
476 proposed by Piva et al. (2011), with slight modifications. The WOE approach was first proposed by  
477 these authors to assess sediment hazard in particular, with a low coefficient (0.3) for bioassays using

478 the water column as a test matrix. In the present study, we apply the procedure to both sediment and  
479 water column hazard assessment. Consequently, we chose to set the coefficient for water column  
480 testing similarly to what was used for sediment testing (*i.e.*, equal to 1 for total water and 0.8 for the  
481 water-dissolved fraction). Moreover, as an ‘ecotoxicologically relevant’ effect was identified for each  
482 marker and as ‘contrary’ effects were discarded from analysis, it seemed superfluous to weight  
483 endpoints according to the possibility of hormetic responses. Details on weighting calculations for  
484 each endpoint are given in ESM Table S8. Finally, the cumulative ToxHQ was calculated as the sum  
485 of the  $E_w(i)$ , and a global hazard class for bioassays was attributed as described by Piva et al. (2011)  
486 (ESM Fig. S4). This hazard quotient was elaborated for each site and each campaign, for the water  
487 column ( $ToxHQ_{water}$ ) and for the sediment ( $ToxHQ_{sed}$ ).

488

#### 489 2.7.5. Weight of Evidence integration

490 The complete calculation procedure implemented for WOE integration is detailed in ESM Fig. S5. As  
491 described by Piva et al. (2011), the first step of the integration of the HQs derived from the four LOEs  
492 within a global index (WOE index) consisted in normalizing HQ values to a common scale. The  
493 authors also proposed to ascribe different weightings to LOE results according to their environmental  
494 relevance. Thus, they chose to multiply BioavHQ indices by 1.2× to give greater importance to  
495 bioavailability data as compared to the presence of chemicals in the abiotic compartment (*i.e.*,  
496 ChemHQs, weighted by 1.0×). Similarly, they suggested to apply a 1.2×-coefficient to the data  
497 acquired using bioassays (ToxHQ indices) because they reflected acute effects at the organism level,  
498 whereas biomarker responses (BiomHQ indices) describing sublethal effects at the molecular scale  
499 remained weighted by 1×. The situation was somewhat different in the present study, since biomarkers  
500 included both responses at the molecular level (*e.g.*, enzyme activity levels) and life history traits (*e.g.*,  
501 feeding behavior and reproduction ability). As a result, it seemed more relevant to apply greater  
502 weightings to the results of the LOE related to disturbances of organisms exposed *in situ* than to  
503 organisms exposed under laboratory conditions. We thus chose to weight the BioavHQ and BiomHQ  
504 indices by 1.2×, whereas ChemHQs and ToxHQ indices were still weighted by 1×.

505 The resulting HQ indices from the four LOEs were summed up and normalized to 100% to yield an  
506 overall WOE hazard index. Finally, each WOE value was assigned to a hazard class, as described by  
507 Piva et al. (2011) (ESM Fig. S5).

508

509

510

## 511 **3. Results and discussion**

### 512 *3.1. Water column and sediment chemistry: LOE#1*

#### 513 3.1.1. Chemical hazard quotient for the water column (ChemHQ<sub>water</sub>)

514 The chemical hazard relative to water column contamination was evaluated according to the  
515 concentrations of 15 pesticides, 2 AKPs, 1 PFAS (PFOS), and 9 MEs measured in the dissolved  
516 fraction. They are listed in ESM Table S1.

517 The concentration of each chemical (ESM Table S9) was used to calculate an integrative  
518 contamination index, ChemHQ<sub>water</sub> (Table 1). The contribution of each class of compounds to the  
519 global chemical hazard is presented in Fig. 2a. These results show that perfluorooctanesulfonic acid  
520 (PFOS) was omnipresent in the area and contributed to 51% (Marnay C4) to 99% (Bougival C2) of the  
521 ChemHQ<sub>water</sub> values. Average PFOS concentrations were above the EQS value of  $6.5 \times 10^{-4}$  µg/L (EC  
522 2013) at all sites and for all sampling campaigns as well as for calculated annual means; the RTR  
523 values increased along the anthropogenic gradient from 1.30-4.37 in Marnay, 4.85-22.8 in Bougival,  
524 and up to 5.88-35.2 in Triel (ESM Tables S1 and S9). At each site, the lowest RTR value was recorded  
525 during the C4 campaign, and the highest during the C1 campaign. In contrast, the contribution of  
526 pesticides increased at each site in the C4 campaign, with values around 48% at Marnay, 24% at  
527 Bougival and 22% at Triel. Among the pesticides, one compound –metazachlor, a chloroacetanilide  
528 herbicide- accounted for almost the total contribution of this class of chemicals (21% to 46%; data not  
529 shown). The contamination gradient previously mentioned for PFOS was also recorded in the case of  
530 metazachlor winter concentrations, with RTR values increasing from 1.55 in Marnay to 2.29 and 2.38  
531 in Bougival and Triel, respectively (ESM Tables S1 and S9). Metazachlor is an herbicide commonly  
532 used in rapeseed crops and usually applied in late August/early September. This substance is  
533 considered as ‘moderately sorbing’, and several months might go by between its application date and  
534 its release in the surrounding waters, depending on the intensity of the rain events and the  
535 hydrodynamic characteristics of the watershed (Passeport et al. 2013).

536 As shown in Fig. 2a, metal elements only contributed noticeably to ChemHQ<sub>water</sub> values at the  
537 downstream sites, with the highest contributions recorded in the C4 campaign (around 11%), as shown  
538 for pesticides. Despite a clear contamination gradient along the Seine river, the dissolved  
539 concentrations of metals did not exceed, or only slightly exceeded their respective EQS at the two  
540 downstream sites, as previously described (Faburé et al. 2015; Lebrun et al. 2015), and in agreement  
541 with previous studies at the same sites (Fechner et al. 2012). Values exceeding the corresponding  
542 reference value were limited and almost strictly related to copper concentrations, with a maximal RTR  
543 value below 1.35 noted in Triel during the autumn campaign (ESM Tables S1 and S9).

544 Following the integration of overall contamination data measured in the water column, the resulting  
545 ChemHQ<sub>water</sub> values obviously reflected the anthropogenic gradient pressure along the Seine River  
546 axis, with values increasing from the Marnay upstream site to the Bougival and Triel downstream sites  
547 (Table 1). As a result, the chemical hazard for the annual average value was classified as ‘moderate’ at  
548 Marnay and as ‘severe’ at the two stations downstream of the Paris agglomeration. Seasonal variations  
549 in water column contamination were also evidenced, with lower ChemHQ<sub>water</sub> values at all sites in  
550 winter (C4), thus downgrading the hazard class for the most impacted sites from ‘severe’ to ‘major’. In  
551 contrast, the highest ChemHQ<sub>water</sub> values were recorded in the fall season (C1) at each station (Table  
552 1), possibly as a consequence of the lower dilution of point source discharges under low flow  
553 conditions in the River Seine.

554

### 555 3.1.2. Chemical hazard quotient for sediment (ChemHQ<sub>sed</sub>)

556 Sediment contamination was assessed based on the concentrations of 1 PFAS (PFOS), 18 PAHs, 8  
557 PCBs, 7 PBDEs, 12 OCPs, and 15 MEs. They are listed in ESM Table S2, and detailed in ESM Tables  
558 S10 and S11).

559 Considering that for some chemicals such as PAHs, PBDEs and DDTs, the reference values were  
560 available both for individual substances and for the total concentrations of the classes of compounds, it  
561 was possible to calculate ChemHQ<sub>sed</sub> values in two different ways (Table 1). The calculation method  
562 strongly influenced the relative contribution of each class of compounds to the calculated global index  
563 (Fig. 2b and 2c). When ‘individual concentrations’ were used, the most contributive chemical family  
564 was PAHs at each site, and sampling time (except for Bougival C1 and Triel C1/C4 samples) with  
565 total contributions varying from 75% to 99% in Marnay, 52% to 74% in Bougival, and 75% to 99% in  
566 Triel (Fig. 2b). Among this class of compounds, the corresponding reference values were widely  
567 exceeded for phenanthrene and pyrene, with RTR values respectively between 3.0-18.9 and 2.9-15.5  
568 in Marnay, 15.6-57.3 and 18.6-75.4 in Bougival, and between 5.7-836 and 12.1-672 in Triel (ESM  
569 Tables S2 and S10). RTR values around 200 were also noted for anthracene and benzo[a]anthracene in  
570 Triel C3 samples (ESM Tables S2 and S10). As in the case of PAHs, OCPs were omnipresent in the  
571 area, with overall contributions reaching 25% at Marnay, 57% at Bougival, and 74% at Triel (Fig. 2b).  
572 These high contribution levels were mainly attributable to heptachlor concentrations that exceeded the  
573 reference value of 0.02 µg/kg dw 7.7- to 16.9-fold in Marnay, 46.7- to 136-fold in Bougival, and 109-  
574 to 487-fold in Triel (ESM Tables S2 and S10).

575 When PAH concentrations were summed (ΣPAHs) and compared to the reference value for total  
576 PAHs, the resulting RTR values were much lower than those described above for individual  
577 substances. They only varied from 0.35 to 1.70 in Marnay, 2.34 to 9.75 in Bougival, and 1.33 to 65.5

578 in Triel samples (ESM Tables S2 and S10). As a result, the contribution of PAHs to ChemHQ<sub>sed</sub>  
579 values was also low, with values around 10% or lower for all samples, except Triel C3 for which  
580 ΣPAHs accounted for about 73% of the calculated hazard quotient (Fig. 2c). Consequently, the global  
581 relative contributions of OCPs and MEs logically increased with this calculation method (Fig. 2c).

582 The reference values for MEs in sediment were only exceeded in downstream samples. These overruns  
583 were systematic and particularly substantial for Cd, Cu, Pb, and Zn, with RTR values reaching 23.8,  
584 34.1, 20.7, and 39.1, respectively (Triel and Bougival samples combined; ESM Tables S2 and S10).  
585 Higher enrichment factors (in relation to the geochemical background) have been reported for these  
586 elements in sediment cores sampled downstream of the Paris conurbation as compared to upstream  
587 and Oise River sites (Le Cloarec et al. 2011). The sites downstream of Paris receive and integrate all  
588 kinds of pollutants that affect the rest of the Seine Basin. They result from industrial (*e.g.*, foundries,  
589 wire factories) and agricultural activities (*e.g.*, the use of CuSO<sub>4</sub> as a fungicide and bactericide in  
590 vineyards), but also intense urbanization (*e.g.*, the use of leaded gasoline, leaching of old Zn roofs  
591 following rainfalls, effluents from waste water treatment plants (WWTPs)) (Le Cloarec et al. 2011;  
592 Ayrault et al. 2012). The situation is particularly worsened at sites such as Triel, situated downstream  
593 of the Oise river confluence: Triel is not only affected by the inputs from the Paris suburbs and  
594 upstream activities, but also by the high industrialization of the Oise basin and one of the most  
595 important sewage plants of the Paris agglomeration, the Seine-Aval WWTP of Achères located on the  
596 banks of the Seine River, between the Bougival and Triel sampling sites (Le Cloarec et al. 2011;  
597 Ayrault et al. 2012).

598 Similarly to what was observed for the water column, the integrative ChemHQ<sub>sed</sub> values clearly  
599 illustrated the expected contamination gradient; however, values calculated using individual substance  
600 concentrations were significantly higher than those calculated using total concentrations (Table 1).  
601 While the hazard class remained 'severe' for the two downstream stations using either calculation  
602 method (for all campaigns and the annual average value), the hazard status at Marnay varied from  
603 'severe' to 'absent' for the C2 sample and from 'moderate' to 'absent' for the C4 sample when the  
604 ChemHQ<sub>sed</sub> value was calculated using individual substances or total concentrations, respectively  
605 (Table 1). The annual average hazard quotient for sediment chemistry was calculated using the mean  
606 concentration of each chemical from the three composite sediment samples collected in the field  
607 during the C1, C3, and C4 campaigns. Depending on the calculation method, the annual average  
608 hazard class at Marnay varied from 'severe' to 'major' (Table 1).

609 According to MacDonald et al. (2000), ΣPAHs can be efficiently used to predict sediment toxicity,  
610 with no substantial difference with toxicity predictions based on individual PAH concentrations.  
611 However, in the approach developed here, the use of the ΣPAHs did not allow us to get access to  
612 information on the individual compounds involved in exceeding the reference value. Identifying them

613 could nonetheless be valuable to identify the specific chemicals involved in the biological effects  
614 highlighted in LOE#3 and LOE#4. The information could also be exploited during further  
615 investigations aimed at identifying the source(s) of this pollution. Moreover, we preferred to adopt the  
616 most conservative and protective approach for aquatic biota as regards the environmental hazard. As a  
617 result, the ChemHQ<sub>sed</sub> values calculated using individual concentrations were kept for the subsequent  
618 step, (*i.e.*, final integration into the WOE index).

619

### 620 3.2. Bioavailability of chemicals: LOE#2

621 Bioavailability Hazard Quotient (BioavHQ) values were calculated according to the bioaccumulated  
622 concentrations of 17 PAHs, 8 PCBs, 1 PBDE, 7 OCPs, and 4 MEs (listed in ESM Table S3, and  
623 detailed in ESM Table S12) in caged gammarids.

624 The relative contributions of each class of chemicals to the global BioavHQ are illustrated in Fig. 3a.  
625 Accumulation levels of organic compounds were not analyzed during the C4 campaign, and PAH and  
626 PBDE data are missing for the C1 campaign, so contributions to the BioavHQ values are only  
627 discussed based on annual average data.

628 Among trace metals, Ni was noticeably accumulated by gammarids exposed *in situ*, namely 1.7- to  
629 5.4-fold higher than the reference level, with no specific variation among sites attributable to the  
630 anthropogenic gradient (ESM Tables S3 and S12). This could result from a non-identified diffuse  
631 contamination source, and/or Ni geochemical background differences between the native region of  
632 gammarids (the Rhône-Alpes region) and the Seine Basin. In the water column, the Ni background  
633 seemed to be slightly lower in the Rhône watershed (mainly between 0.58 and 2.51 µg/L, and more  
634 locally up to 3.93 µg/L) than in the Seine Basin (2.51-3.93 µg/L), according to the FOREGS  
635 Geochemical Baseline Mapping Program (<http://weppi.gtk.fi/publ/foregsatlas/>). Thus, while Ni locally  
636 reached similar background levels in the Rhône watershed as in the Seine Basin, the globally lower Ni  
637 geochemical background in the Rhône Basin may partially explain the higher Ni bioaccumulation  
638 levels in transplanted gammarids. Yet excess Ni as compared to the reference value reflected an  
639 increase in the Ni bioavailable fraction between the two areas whatever the exact origin (higher  
640 geochemical background and/or anthropogenic activities).

641 In contrast, whereas RTR values for Pb accumulation at Marnay remained around or below 1 (annual  
642 average: 0.94), they ranged between 1.7 and 7.8 in Bougival, and between 1.8 and 3.8 in Triel (ESM  
643 Tables S3 and S12), reflecting a significant increase in Pb bioaccumulation in gammarids downstream  
644 of Paris. Nevertheless, metals contributed only little (< 10%; Fig. 3a) to the annual average BioavHQ  
645 values of the downstream sites. As a result, ME accumulation in gammarids exposed along the Seine  
646 axis represented a limited hazard in comparison to organic compounds, as showed by the RTR<sub>w</sub>-based

647 hazard status mainly evaluated as ‘absent’ or ‘slight’ for MEs (only one ‘major’ status and one  
648 ‘moderate’ status were recorded for Ni accumulation; ESM Table S3).

649 The annual average RTR<sub>w</sub>-based hazard classification was ‘absent’ for all organic compounds at  
650 Marnay (except for PCB 118 classified as ‘slight’), whereas bioavailability-related hazard reached the  
651 ‘major’ to ‘severe’ grade at the downstream stations (ESM Table S3). More specifically, PAHs  
652 accounted for up to 87% and 72% in the calculation of annual average BioavHQ values in Bougival  
653 and Triel, respectively. Still considering annual average data, all PAHs significantly accumulated (at  
654 least 2.5-fold; ESM Tables S3 and S12) in gammarids exposed at Bougival as compared to the  
655 reference levels. Among these compounds, respective reference bioaccumulation levels were exceeded  
656 around 10-fold or just above for acenaphthene, anthracene, benzo[e]pyrene and phenanthrene, nearly  
657 20-fold for benzo[a]anthracene and chrysene/triphenylene, and an extreme >30-fold for fluoranthene  
658 and pyrene (ESM Tables S3 and S12). Annual average RTR values were lower in Triel-exposed  
659 gammarids, mainly falling between 1.2 and 9.2 (ESM Tables S3 and S12). Bioaccumulation levels  
660 more than 10-fold the reference values were only recorded for fluoranthene (11.1×) and pyrene  
661 (15.4×) at that site (ESM Tables S3 and S12), confirming that these compounds were the most  
662 bioaccumulated ones when compared to the reference levels.

663 These results are in overall agreement with the PAH concentrations measured in sediment, since  
664 particularly high RTR values were recorded for anthracene, phenanthrene, benzo[a]anthracene, and  
665 pyrene (see Section 3.1.2). However, PAH bioaccumulation levels were higher at Bougival than at  
666 Triel, whereas PAHs were globally more abundant in Triel sediment than in Bougival sediment  
667 (organic carbon-normalized concentrations increased 1.7-fold to 5.4-fold between the two sites  
668 depending on the sampling campaign; ESM Table S11). This was likely related to variations in PAH  
669 bioavailability between the two sites.

670 PCBs ranked second among the chemicals contributing to the annual average BioavHQ values at the  
671 downstream sites, *i.e.* 11% in Bougival and 15% in Triel (Fig. 3a). The annual average RTR values  
672 ranged between 2.7 and 6.7 in Bougival, and between 2.5 and 5.1 in Triel, depending on the congener  
673 (ESM Tables S3 and S12). As a result, the RTR<sub>w</sub>-based hazard was ‘moderate’ for PCB 50+28, PCB  
674 52 and PCB 101, and ‘major’ for PCB 118 in Bougival (ESM Table S3). As regards Triel, only PCB  
675 101 and PCB 118 accumulation levels represented a substantial hazard (*i.e.*, above the ‘slight’ status)  
676 evaluated as ‘moderate’ and ‘major’, respectively.

677 The overall LOE#2 results tend to suggest that PAHs were the main problematic class of compounds  
678 regarding their potential bioavailability/bioaccumulation in aquatic organisms in the two stations  
679 located downstream of Paris.



680 The integration of overall bioavailability data resulted in lower BioavHQ values for the winter  
681 campaign (C4) at all sites (Table 2). The hazard associated with bioaccumulation levels was  
682 consequently evaluated as ‘slight’ for this campaign. However, the conclusion on the C4 campaign  
683 should be interpreted carefully because it was only based on ME accumulation, and ME accumulation  
684 proved to be limited as compared to organic compounds at the other sampling periods.

685 With BioavHQ values varying between 1.8 and 13.4, the related hazard was also classified as ‘slight’  
686 in Marnay for each sampling period as well as for the annual average value (Table 2). In contrast, the  
687 highest BioavHQ values were recorded in Bougival (except for C4) and the associated hazard was thus  
688 evaluated as ‘major’ (Table 2). The hazard was also identified as ‘major’ during the fall campaign  
689 (C1) at Triel; however, it decreased to ‘moderate’ for the other campaigns (C2 and C3) as well as for  
690 the annual average BioavHQ (Table 2).

691

### 692 3.3. Biomarker responses in gammarids exposed *in situ*: LOE#3

693 Biological responses in gammarids exposed *in situ* along the Seine axis were investigated using  
694 several biomarkers of various physiological impairments, including neurotoxicity, energy acquisition  
695 disturbance, feeding behavior impairment, reproduction dysfunctioning/failure, and survival (ESM  
696 Table S13). These markers have been studied in our laboratories for several years and are commonly  
697 used in laboratory and field experiments (Dedourge-Geffard et al. 2013; Xuereb et al. 2009; Geffard et  
698 al. 2010; Coulaud et al. 2011; Charron et al. 2013; Chaumot et al. 2015). The substantial insights  
699 gained from these numerous studies more particularly allowed us to (i) fully determine the basal level  
700 and variation range of each marker, (ii) identify and characterize the confounding factors that may  
701 modulate biomarker responses, especially under field conditions, and thus (iii) determine specific  
702 reference levels and effect thresholds for these biomarkers adapted to *in situ* deployment conducted in  
703 the context of an environmental survey (ESM Table S4). These reference values and thresholds were  
704 used to calculate biomarker Hazard Quotients (BiomHQs) applied to the Seine axis case study (Table  
705 3).

706 The contribution of each category of markers to the calculated BiomHQ values is illustrated in Fig. 3b.  
707 This analysis is completed by the hazard class attributed to each biomarker response, presented in  
708 ESM Table S5.

709 No sign of neurotoxicity was highlighted: no significant inhibition of AChE activity was recorded in  
710 comparison to the established reference value (ESM Tables S4 and S13); the hazard relative to the  
711 AChE marker was ‘absent’ for all sites and all sampling campaigns (ESM Table S5).

712 Unlike AChE activity, the decrease in gammarid survival represented a ‘severe’ hazard at all sites and  
713 all sampling periods (ESM Table S5), except in the C4 campaign during which no significant  
714 mortality was noted (<4% in all stations; ESM Table S13). This acute toxicity endpoint was the only  
715 that showed an effect E(i) above 1 at Marnay (representing a 1.8- to 3.2-fold increase in comparison to  
716 the reference value, ESM Tables S4 and S13), therefore it contributed 100% to the calculated  
717 BiomHQ value for that station (Fig. 3b). The impact on gammarid survival at Marnay raises the  
718 question whether some early (sublethal) responses of other physiological functions, not addressed in  
719 the present study, could potentially exist. For instance, studying the impacts of exposure on the  
720 immune system and the inflammatory mechanisms could be of great interest by bringing supplemental  
721 data to the currently investigated biomarkers. Due to their direct implications in individual fitness,  
722 population and ecosystem health (Bols et al. 2001), immunomarkers are considered as attractive non-  
723 specific markers that could be consistently integrated into ERA and biomonitoring surveys (Bado-  
724 Nilles et al. 2015).

725 Mortality was modulated in the same order of magnitude at the downstream sites as at Marnay, with a  
726 1.5- to 2.5-fold rise at Bougival, and a 1.6- to 3.0-fold rise at Triel (ESM Tables S4 and S13).  
727 However, it resulted in contributions to BiomHQ values that were more limited than at Marnay and  
728 ranged between 43% to 61% at Bougival, and 32% to 45% at Triel (Fig. 3b). Several other markers  
729 were significantly modulated in the gammarids exposed at the two downstream sites.

730 Digestive enzyme activities were particularly down-regulated in the C1 and C3 sampling periods, but  
731 were not significantly modulated during the winter (C4) campaign (‘absent’ hazard for all markers;  
732 ESM Table S5). Overall, inhibition of enzymatic activities ranged between 17% and 37% at Bougival  
733 and Triel during the fall (C1) and summer (C3) campaigns (ESM Tables S4 and S13). Special cases  
734 were recorded at Bougival: no significant inhibition of cellulase activity was noted during the C3  
735 campaign, whereas trypsin inhibition increased by 60% of the reference value at the same time (ESM  
736 Tables S4 and S13). Still based on the digestive enzyme activities, the annual hazard (assessed by  
737 averaging the effect E(i) of the three sampling periods) related to energy acquisition parameters was  
738 evaluated as ‘moderate’ at Bougival, and ranked from ‘moderate’ to ‘severe’ at Triel (ESM Table S5).  
739 However, this class of markers only slightly contributed to the global hazard related to biomarker  
740 responses, with a maximal contribution barely exceeding 20% for the Triel C3 sampling point (Fig.  
741 3b).

742 In contrast to energy acquisition markers, feeding rates were the most severely inhibited in gammarids  
743 exposed to the downstream stations during the winter (C4) campaign, with values representing 92%  
744 and 79% decreases in comparison to the corresponding reference value at Bougival and Triel,  
745 respectively (ESM Tables S4 and S13). These effects accounted for 100% of the calculated BiomHQ  
746 at the downstream sites during the C4 sampling period, and represented a ‘severe’ hazard (Fig. 3b,

747 ESM Table S5). Gammarid feeding activity was also repressed during the summer campaign, up to  
748 21% at Bougival ('moderate' hazard) and 49% at Triel ('severe' hazard'). As a result, a 'major' annual  
749 hazard was attributed to the effects on feeding behavior in gammarids exposed downstream of Paris  
750 (ESM Table S5).

751 Among the reproductive impairment biomarkers, the number of oocytes *per* female did not decrease in  
752 gammarids exposed along the Seine axis. Inversely, *in situ* exposure yielded values up to 2-fold higher  
753 than the expected value (ESM Tables S4 and S13). Therefore the environmental hazard associated to  
754 this marker was 'absent' for all sites and all campaigns (ESM Table S5). However, the number of  
755 embryos *per* female decreased by 33% at Bougival and 71% at Triel during the C1 campaign (ESM  
756 Tables S4 and S13), representing a 'severe' potential hazard to aquatic organisms (ESM Table S5).  
757 Even more pronounced impacts were highlighted on molt delay, which noticeably increased during all  
758 campaigns, by 27% to 57% at Bougival and by 40% to 50% at Triel (ESM Tables S4 and S13). The  
759 overall environmental hazard was classified as 'severe' for both stations for this reproductive marker  
760 (ESM Table S5). Reproductive impairments consequently represented the second most contributive  
761 class of biomarkers to BiomHQ values for the C1 and C3 campaigns and the annual average value,  
762 with contributions varying between 20% and 40-45% at Bougival and Triel (Fig. 3b).

763 All biomarkers were finally integrated into a global hazard quotient. The resulting BiomHQ values  
764 clearly depicted the expected anthropogenic gradient, with values increasing from Marnay to Bougival  
765 and then Triel, for each sampling campaign as well as for the annual average value (Table 3). The  
766 lowest BiomHQ was recorded in the C4 campaign at all sites; the hazard was classified as 'slight'  
767 (Marnay) or 'major' (Bougival, Triel). However, as in the case of bioavailability, these results should  
768 be interpreted carefully because reproduction markers and cellulase activity were not investigated  
769 during that campaign. The C4 data did not fulfil the minimum requisite advised by Piva et al. (2011) to  
770 calculate the cumulative BiomHQ: only two markers had a weighting above 1.2, while the  
771 recommended number is 3. Conversely, the highest BiomHQ values were noted in the fall (C1)  
772 campaign (Table 3). This observation is consistent with the water column and sediment ChemHQ  
773 values (using 'total concentrations'), which were also higher in C1 samples. In agreement with the  
774 hazard class established from the other sampling periods, the overall level of risk (based on annual  
775 average estimation) was identified as 'moderate' at Marnay, 'major' at Bougival, and 'severe' at Triel  
776 (Table 3), reflecting a noticeable increase of physiological disturbances in gammarids exposed along  
777 the Seine axis. A similar gradient of biological effects was reported in caged zebra mussels following  
778 exposure at the same sampling sites in winter, spring, and summer (Michel et al. 2013). Genotoxicity  
779 markers (DNA strand breaks and micronucleus frequency) significantly increased from Marnay to  
780 Bougival and then Triel. Seasonal variations of the responses were also highlighted for DNA strand  
781 breaks, with the lowest levels recorded in winter as compared to summer and spring (Michel et al.  
782 2013). All these observations are in good agreement with the conclusions drawn from our LOE#3

783 integration results, suggesting that the effect gradient and seasonal trends (with lower biological  
784 disturbances in winter) are constant year in, year out.

785 Overall, our results demonstrate that the selected set of biomarkers efficiently reflected biological  
786 disturbances in gammarids following exposure along the Seine axis. The use of markers at different  
787 levels of biological organization, from the molecular level to life history traits, allowed us to  
788 discriminate among sites and observations. It also highlighted that *in situ* exposure differentially  
789 affected various physiological mechanisms depending on the level of anthropogenic pressure and the  
790 sampling period, thus demonstrating the complementarity of the selected endpoints. The reference  
791 values and biomarker thresholds used in the present study were specifically established according to  
792 the characteristics of the transplanted gammarid population (*e.g.*, size and weight) and some abiotic  
793 exposure parameters (*e.g.*, temperature). The use of such reference values and thresholds improved the  
794 reliability of the environmental diagnosis by integrating response variations due to the physiological  
795 state of gammarids and/or to field exposure conditions other than chemical pressure. Such finer  
796 characterization of the reference state is clearly needed when biological responses following  
797 seasonally varying contamination are studied. It can therefore be assumed that site qualification in  
798 terms of environmental hazard/risk is more relevant and robust using these adaptive references rather  
799 than more generic ones. For example, a 20-30% inhibition threshold for AChE activity is generally  
800 admitted in the literature for freshwater and marine invertebrates (Escartín and Porte 1996; Owen et al.  
801 2002), but the value established and used in the present study was substantially lower (12%) (Xuereb  
802 et al. 2009). This type of methodology could be applied to responses analyzed within other LOEs such  
803 as bioavailability and bioassays, to refine and adjust the conclusions of the strategy (*e.g.*, a WOE  
804 approach) implemented to describe the ecological state of an aquatic environment.

805

### 806 3.4. Laboratory bioassays: LOE#4

807 The ecotoxicological diagnosis of the area was completed using a battery of laboratory bioassays  
808 performed on water column and sediment samples whose responses were integrated into the WOE  
809 approach to calculate cumulative hazard indices (ToxHQs) in the two abiotic compartments.

810

#### 811 3.4.1. Bioassay hazard quotient in the water column (ToxHQ<sub>water</sub>)

812 Aqueous samples were tested for embryotoxicity and teratogenicity using MELA (dissolved fraction)  
813 and for endocrine-disrupting potency using cellular *in vitro* bioassays on organic extracts. Responses  
814 were selected among the various endpoints monitored during the MELA according to their reliability,  
815 relevance and sensitivity to characterize survival (embryonic and larval survival rates), *in ovo*

816 development (hatching success and time to hatch) and growth (total body length and head size at  
817 hatching), and teratogenicity (total percentage of abnormal larvae). These responses (ESM Table S14)  
818 were integrated into the WOE approach to calculate  $ToxHQ_{water}$  indices for each site and each  
819 sampling period (Table 4). The contributions of the different classes of endpoints to the global hazard  
820 quotient are shown in Fig. 4a.

821 Exposure of medaka ELS early life stages (ELS) to the dissolved fraction of the water samples  
822 collected at Marnay did not induce strong deleterious effects. Only a slight decrease (around 7%) in  
823 embryonic and larval survival rates exceeding the established thresholds was recorded in the C1  
824 campaign (ESM Tables S7 and S14). Similarly, a slight reduction of the total body length of larvae at  
825 hatching was noted in medaka exposed to C1 and C3 samples, representing less than a 4% fall in  
826 comparison to the reference value (ESM Tables S7 and S14). The greatest modulations as compared to  
827 the reference at Marnay were highlighted by ER induction factors exceeding the corresponding  $Th$   
828 value by 4.3- to 5.6-fold (ESM Tables S7 and S14). However, ER agonist activity was only evaluated  
829 as significant (in comparison to the blank) in the C3 samples (ER induction factor: 3.26 $\times$ ; ESM Table  
830 S14). As a result, survival, growth, and endocrine disruption were the most contributive classes of  
831 endpoints to the global hazard quotient in bioassays on water column samples from Marnay (Fig. 4a).  
832 In agreement with this limited effect, the  $ToxHQ_{water}$  values were low ( $< 5$ ) at Marnay, and the  
833 resulting hazard class for bioassays was 'absent' for all sampling periods as well as for the annual  
834 average value (Table 4).

835 Similar results were obtained for the Bougival C3 and C4 samples, with only slight effects on survival,  
836 growth, and estrogenic potency (ESM Table S14), so that the resulting hazard was classified as  
837 'absent' for these periods (Table 4). In contrast, the C1 water sample from that station proved much  
838 more problematic as it strongly increased embryonic mortality (46%), and to a lesser extent larval  
839 mortality (14%) (ESM Table S14). Similarly, hatching success was reduced by 50% in comparison to  
840 the control. Teratogenicity also increased 4.4-fold as compared to the reference value, so that more  
841 than 80% of the hatchlings exhibited developmental abnormalities (ESM Tables S7 and S14).  
842 Additionally, ER activity was between 6.1 and 9.2 times higher than the established  $Th$  value (ESM  
843 Tables S7 and S14). However, these endocrine-disrupting effects did not contribute much to the global  
844 hazard (2%) because survival, development and teratogenicity accounted for 63%, 16% and 12% of  
845 the calculated  $ToxHQ_{water}$ , respectively (Fig. 4a). These effects account for the downgrading of the  
846 hazard associated to bioassay responses to the 'moderate' status (very close to the 'major' class) for  
847 the C1 campaign at Bougival. Nevertheless, in relation to the biological responses recorded in the fall  
848 (C1) campaign, the annual average hazard class was classified as 'slight' at Bougival (Table 4).

849 The Triel response profile was quite similar to that of Bougival, yet more pronounced. Bioassays on  
850 water samples from the winter (C4) campaign only revealed an impact on ED parameters, with

851 induction of ER activity 6.5-fold higher than the reference value (11 times the Th level; ESM Tables  
852 S7 and S14). A slight induction of the AR/GR agonist activity was also noted, but it only represented a  
853 1.83-fold increase as compared to the reference level (ESM Tables S7 and S14). These responses  
854 accounted for 74% of the cumulative  $ToxHQ_{water}$  in Triel-C4 (Fig. 4a), but resulted in a global hazard  
855 classified as ‘absent’ (Table 4). ER and AR/GR agonist activities were induced with the same order of  
856 magnitude following cell exposure to Triel-C1 water organic extract (10.4× and 1.9× the  
857 corresponding Th value, respectively; ESM Tables S7 and S14). However, endocrine-disrupting  
858 effects only accounted for 7% of the calculated  $ToxHQ_{water}$  at that site (Fig. 4a), as stronger impacts  
859 were detected in medaka ELS following exposure to the dissolved fraction of the water sample  
860 collected at Triel during the fall campaign. As observed for Bougival during the same sampling  
861 campaign, exposure led to a strong increase of the mortality rate of exposed embryos (only one third  
862 of the embryos were still alive at the end of the experiment; 13.3 times the Th value; ESM Tables S7  
863 and S14). Moreover, hatching success was reduced by more than 70% in comparison to the control (~7  
864 times the Th value), and the mean time to hatch was delayed by about 25.5% (1.6 times higher than  
865 the Th value) as compared to the reference (ESM Tables S7 and S14). An impact on medaka *in ovo*  
866 development was also reflected by the total body length of hatchlings, which was reduced by 5.4% in  
867 comparison to control organisms (about 4 times the Th value; ESM Tables S7 and S14). However, this  
868 effect on *in ovo* growth was quite limited as it only accounted for 7% of the global hazard quotient  
869  $ToxHQ_{water}$ , whereas survival and development alterations respectively accounted for 61% and 25%  
870 (Fig. 4a). The resulting hazard attributed to the  $ToxHQ_{water}$  index for Triel-C1 was identified as  
871 ‘major’ (Table 4). The growth of medaka embryos exposed to the Triel-C3 water sample was also  
872 slightly reduced: larvae were 3.4% shorter than the controls (2.4 times the Th value; data not shown).  
873 Nevertheless, the summer (C3) sample from Triel was particularly marked by a strong induction of  
874 both ER and TR activities, exceeding the corresponding Th values by 21.8× and 25.6× respectively  
875 (equivalent to respective induction factors of 11.9 and 13.8 as compared to the control; ESM Tables  
876 S7 and S14). As a result, endocrine-disrupting effects contributed to 80% of the cumulative  
877  $ToxHQ_{water}$  calculated for Triel-C3 (Fig. 4a), and the global hazard evaluated using bioassays was  
878 summarized as ‘slight’ (Table 4). Annual averaging of the effects observed during bioassays resulted  
879 in a global  $ToxHQ_{water}$  classifying the hazard as ‘slight’ (but very close to the ‘moderate’ class) for  
880 Triel (Table 4). The  $ToxHQ_{water}$  value was mainly due to impacts on survival (44%) and *in ovo*  
881 development (19%) of medaka ELS, as well as to endocrine-disrupting effects (27%) on specific cell  
882 lines (Fig. 4a).

883

884 3.4.2. Bioassay hazard quotient of sediment ( $ToxHQ_{sed}$ )

885 As in the case of the water column, ED assays were performed on sediment organic extracts, and the  
886 MELAc (MELA adapted to sediment testing by direct contact with particles) was implemented on  
887 whole sediment samples. In addition, cytotoxicity and genotoxicity of sediment elutriates were  
888 investigated using the Microtox and SOS Chromotest procedures, respectively. As previously  
889 mentioned, the responses of all the bioassays (ESM Table S14) were integrated into a common hazard  
890 quotient,  $ToxHQ_{sed}$  (Table 4), and the contribution of each endpoint class to the hazard index was  
891 calculated (Fig. 4b).

892 Medaka exposure to Marnay sediments only resulted in limited sublethal effects on fish ELS. A slight  
893 delay in the average time to hatch of embryos was noted following exposure to the sediment sampled  
894 during the three campaigns (C1, C3 and C4), representing 2 to 5% variation in comparison to the  
895 control values (ESM Tables S7 and S14). Moreover, a significant increase in the percentage of  
896 abnormal larvae at hatching (around 2 times higher than the control, *i.e.*, around 35.5% of abnormal  
897 individuals; ESM Tables S7 and S14) was noticed after exposure to Marnay sediment collected during  
898 the fall (C1) period. *In ovo* growth of embryos exposed to C3 and C4 samples also slightly decreased:  
899 biometric measurements were lower than the reference values, especially hatchling head size for  
900 which the highest percentage of variation relative to the control was recorded (~8%; ESM Tables S7  
901 and S14). The cytotoxicity of sediment elutriates remained moderate for Marnay C3 and C4 samples  
902 (less than 30% inhibition of bioluminescence), but was greater during the fall (C1) campaign with  
903 50% inhibition (ESM Tables S7 and S14). The strongest effects were noted for ER agonist activity of  
904 sediment organic extracts, which noticeably increased by 8.5- and 9-fold, following exposure to C3 and  
905 C1 organic extracts, respectively, and to a lesser extent following exposure to the C4 sample (4×)  
906 (ESM Tables S7 and S14). As a result, development, growth, endocrine disruption, and cytotoxicity  
907 were the most contributive endpoint classes to the global hazard quotient  $ToxHQ_{sed}$ . They accounted  
908 for 26%, 28%, 18%, and 18% of the annual average calculation of  $ToxHQ_{sed}$ , respectively (Fig. 4b).  
909 The resulting hazard was summarized as ‘slight’ at Marnay for all the sampling periods as well as for  
910 the annual average value (Table 4).

911 The bioassay response profiles at the Marnay and Bougival stations were very similar, as illustrated by  
912 the endpoint contributions to the  $ToxHQ_{sed}$  values (Fig. 4b). However, the response was clearly greater  
913 downstream of Paris. For example, the time to hatch of embryos exposed to Bougival C3 sediment  
914 was 24% longer than in the control treatment, and more than 50% of the larvae showed developmental  
915 abnormalities on average following exposure to Bougival C1 sediment (ESM Tables S7 and S14).  
916 Whereas elutriates from the Bougival fall (C1) and winter (C4) samples inhibited bioluminescence by  
917 around 40%, the Bougival C3 elutriate reduced it by up to 96% as compared to the reference value  
918 (ESM Tables S7 and S14). Similarly, TR and AR/GR agonist activities as well as AR antagonist  
919 activity were enhanced with Bougival samples as compared to Marnay samples: they exceeded the  
920 established respective  $Th$  values by 2.1× to 4.3×. As observed for Marnay, ER agonist activity showed

921 the greatest induction as compared to the reference level: between 7.7-fold in the winter (C4)  
922 campaign and 32-fold in the summer (C3) campaign (ESM Tables S7 and S14). As a result, the  
923  $ToxHQ_{sed}$  values for Bougival were higher than for Marnay. While the global hazard remained  
924 classified as ‘slight’ for the C1 and C4 campaigns (although close to the ‘moderate’ hazard limit;  
925 Table 4), it reached the ‘moderate’ grade for Bougival C3 due to the strong effects highlighted by  
926 bioassays. In agreement with these observations, the annual global hazard associated with bioassay  
927 responses was summarized as ‘moderate’ for Bougival (Table 4).

928 According to bioassay endpoints, the greatest toxicity was recorded at Triel. Signs of acute toxicity  
929 were highlighted in medaka ELS following exposure to C1 and C3 sediment: embryonic survival  
930 decreased by 13% as compared to the reference value in Triel C1, and hatching success did not exceed  
931 1.3% and 0% in Triel C1 and C3, respectively (ESM Tables S7 and S14). Moreover, the few resulting  
932 hatchlings finally died before the end of the experiment (data not shown). Consequently, teratogenicity  
933 and *in ovo* growth were only evaluated for the Triel winter (C4) sample. Forty-nine percent of the  
934 larvae exposed to this sediment displayed developmental deformities, and their growth was reduced by  
935 8% to 9% depending on the endpoint (ESM Tables S7 and S14). The cytotoxicity of Triel elutriates  
936 was very high in the C1 and C3 samples: bioluminescence was inhibited by 96% and 94%.,  
937 respectively. In contrast, cytotoxicity was very limited in the Triel C4 sample: only 25% inhibition of  
938 bacteria bioluminescence was noted (ESM Table S14). Modulation of endocrine-disrupting responses  
939 following cell line exposure to Triel sediment organic extracts was of the same order of magnitude as  
940 in Bougival sediment. TR, AR/GR and Anti-AR activity induction exceeded the respective  $Th$  values  
941 by 1.9- to 5.3-fold, depending on the endpoint and the campaign (ESM Tables S7 and S14). In  
942 addition, ER agonist activity modulation was the strongest, with induction factors ranging between  
943 4.1-fold in the winter (C4) campaign and 30-fold in the summer (C3) campaign (ESM Tables S7 and  
944 S14). Unsurprisingly, the hazard for toxicity assessed through laboratory bioassays was evaluated as  
945 ‘severe’ for Triel C1 and C3 sediment (Table 4). The survival and development endpoint classes  
946 respectively accounted for 51% and 28% of the global  $ToxHQ_{sed}$  value in Triel C1. Development  
947 (47%), cytotoxicity (23%), and endocrine disruption (20%) were the most contributive endpoint  
948 classes to the Triel C3  $ToxHQ_{sed}$  value, whereas growth (41%) and teratogenicity (30%) accounted for  
949 the main part of the Triel C4  $ToxHQ_{sed}$  value (Fig. 4b). Due to the limited effects of this latter sample,  
950 the corresponding hazard was evaluated as ‘slight’. Finally, based on bioassay responses we concluded  
951 that Triel sediment represented a ‘major’ yearly hazard (Table 4).

952 Overall, the  $ToxHQ$  values calculated for the water column and the sediment clearly reflected the  
953 anthropogenic gradient between the upstream and downstream sites, with values increasing from  
954 Marnay to Bougival and Triel (Table 4), similarly to biomarker responses (see Section 3.3). Moreover,  
955 the yearly variations of bioassay responses identified the C1 and C3 water and sediment samples as the  
956 most toxic, whereas C4 samples only induced limited effects. These observations are in good



957 agreement with the conclusions drawn from bioavailability and biomarker LOEs (see Sections 3.2 and  
958 3.3). Moreover, the independent exposure of model organisms/cell lines to water column or sediment  
959 samples gave new insights into environmental contamination along the Seine River. The main part of  
960 the toxic effects we noted appeared to be associated with the sediment compartment since the hazard  
961 class indices in sediment were systematically higher than in water samples (Table 4).

962 Our results clearly show that the sediment compartment should be integrated into environmental  
963 quality assessment procedures as a potential non-negligible source of toxicity for aquatic organisms.  
964 Such procedures only based on water column analysis could underestimate the (eco)toxicological risk  
965 for ecosystems.

966 The accuracy and environmental significance of toxic responses based on laboratory bioassays (and of  
967 the resulting hazard assessment) could be improved by working on the reference and threshold values.  
968 Many bioassays, such as *in vitro* tests, presently use ‘too clean to be real’ standards as negative  
969 controls (*e.g.*, extraction blanks, ultra-pure water, etc.). The establishment of ‘truly environmental’  
970 negative controls should be closely investigated to make these bioassay responses more realistic and  
971 relevant in an environmental context. The calculation of reference and threshold values from the  
972 analysis of environmentally ‘clean’ water and sediment samples could be a valuable alternative to  
973 characterize the basal levels and variations of very specific responses such as hormone-mimetic,  
974 genotoxicity, and cytotoxicity endpoints. We applied this kind of approach in some bioassays such as  
975 the MELA (and the MELAc), with drinking water and Yville-sur-Seine sediment (a pristine site in the  
976 vicinity of the Seine River axis) as negative controls for water and sediment samples, respectively.  
977 The integration of other reference matrices from various geographical localizations could also make it  
978 easier to understand response variability by taking into account the natural diversity and heterogeneity  
979 of the reference environments.

980 Such a strategy would undoubtedly improve the accuracy and the relevance of environment quality  
981 assessment using laboratory bioassays in large-scale studies as well as in more geographically-  
982 restricted contexts with locally contrasted areas.

983

### 984 3.5. WOE integration

985 The results of each LOE were integrated into a global WOE index, and a hazard class was attributed to  
986 each site and campaign (Fig. 5). Moreover, the contribution of each HQ index to the WOE value was  
987 calculated, and is presented in Fig. 6.

988 WOE levels clearly reflected the anthropogenic gradient along the Seine River, with values increasing  
989 from upstream to downstream of Paris (Fig. 5). They were systematically lower at Marnay (15% to

990 30%), intermediate at Bougival (38% to 64%) and the highest at Triel (39% to 70%) for all campaigns  
991 and for annual average values. The only exception was the spring (C2) sampling period for which the  
992 highest WOE index was noted at Bougival (Fig. 5). The resulting hazard classes varied from 'slight' to  
993 'moderate' at Marnay, and from 'moderate' to 'major' at the two stations located downstream of Paris,  
994 and the WOE index of Triel C1 was very close to the 'severe' hazard level. The year-round hazard was  
995 assessed using the annual average LOE data. It summarized the overall hazard class as 'moderate' at  
996 Marnay and 'major' at Bougival and Triel (Fig. 5).

997 Additionally, the seasonal variations identified when examining the results of each LOE were also  
998 reflected in the WOE levels. The lowest value was consistently recorded for the winter (C4) campaign,  
999 at each site. In contrast, the fall (C1) and summer (C3) campaigns had previously been identified as  
1000 the most impacted ones, and coherently resulted in the highest WOE levels (Fig. 5). The only  
1001 exception was the Bougival C2 sampling point; however, it should be borne in mind that the hazard  
1002 assessment during the spring campaign was only based on bioaccumulation and water contamination  
1003 data. For this reason, contributions of HQ indices are not discussed below because they are biased by  
1004 the missing C2 campaign data.

1005 The contribution profiles from Marnay revealed that chemical contamination in the abiotic  
1006 compartment was the main component of the WOE index, with a global contribution ( $\text{ChemHQ}_{\text{water}}$   
1007 plus  $\text{ChemHQ}_{\text{sed}}$  contribution) around 80% for each sampling period and the annual average value  
1008 (Fig. 6a). At the upstream site, the greatest risk was attributable to the contaminants analyzed in the  
1009 sediment: the contributions of the  $\text{ChemHQ}_{\text{sed}}$  indices reached 60% (vs. around 20% for the  
1010  $\text{ChemHQ}_{\text{water}}$  indices). Similar observations were made for the downstream stations during the winter  
1011 (C4) campaign. The global contribution of chemicals in the abiotic compartment also represented  
1012 around 80% for Bougival and Triel during the C4 campaign; however, the contributions of water  
1013 column and sediment contamination were almost the same, indicating that the chemical hazard was  
1014 governed by contaminants analyzed in the water column as well as in the sediment at both downstream  
1015 sites (Fig. 6b and 6c). The cumulative contributions of ChemHQs were also substantial at the  
1016 downstream stations during the C1 and C3 campaigns, and the annual average values ranged between  
1017 48% and 62% (Fig. 6b and 6c). However, biological effects recorded *in situ* (BiomHQs) and under  
1018 laboratory conditions (ToxHQs) also contributed to the calculated WOE value in a non-negligible  
1019 way. Biomarker responses thus accounted for 11% to 17% of the WOE indices, and bioassays  
1020 contributed between 16% to 36% (Fig. 6b and 6c). Among the bioassays, the ones using sediment as a  
1021 test phase usually yielded the highest contributions, suggesting again that the sediment compartment  
1022 represents a noticeable hazard in terms of both contamination levels and biological effects.

1023 The increase of the biological effects noted at some particular sites/sampling dates, such as Triel  
1024 C1/C3, could be attributed to seasonal variations in the contamination levels, as revealed by LOE#1

1025 results. The concentrations of some contaminants such as PFOS and pesticides are clearly influenced  
1026 by seasonal factors such as hydrological conditions (Tamtam et al. 2008; Labadie and Chevreuil 2011)  
1027 and/or by the seasonal use of certain chemicals such as pesticides, including metazachlor (Passeport et  
1028 al. 2013).

1029 Moreover, the levels of metal elements in gammarids revealed that bioaccumulation was influenced  
1030 not only by the contamination levels but also by seasonal variables like temperature, especially  
1031 concerning essential elements (Lebrun et al. 2015). A more accurate characterization and  
1032 understanding of these variations would make it possible to refine the reference values and/or to define  
1033 specific thresholds according to the substance and the influence of confounding factors on its  
1034 accumulation levels in organisms. For instance, determining whether the temperature influenced  
1035 bioaccumulation levels by modulating metabolic rates or contaminant bioavailability would be of great  
1036 interest. These adjustments could improve the conclusions of the WOE procedure in a relevant and  
1037 reliable way, by monitoring the impact of external abiotic factors likely to modulate the time-course of  
1038 accumulation by exposed organisms, especially in close but contrasted areas.

1039 Overall, the conclusions on the hazard represented by ‘chemical’ and ‘biological’ LOEs (*i.e.*, LOEs#1-  
1040 2 vs. LOEs#3-4) are relatively coherent, although a shift in hazard severity was evidenced between the  
1041 two types of LOEs. In fact, the hazard level is generally lower with ‘biological’ LOEs than with  
1042 ‘chemical’ LOEs (Fig. 5). The table at the bottom of Fig. 5 also reveals a few exceptions (*e.g.*, Triel  
1043 C4) for which the conclusion of the chemical and biological LOEs were not fully consistent,  
1044 suggesting that the two approaches are complementary. These observations also emphasize the  
1045 usefulness of WOE integration, as the class-based hazard ranking of the sites differed when  
1046 considering the results of each LOE independently, especially at the downstream sites. For instance,  
1047 when referring to the annual hazard class associated to ChemHQ<sub>sed</sub> values, we failed to discriminate  
1048 among the three sites because the environmental hazard was evaluated at the highest level (‘severe’) in  
1049 all cases (Table 1), indicating that all sites represented the maximal hazard level in terms of sediment  
1050 contamination. In contrast, the annual average hazard classes associated to sediment bioassays  
1051 (ToxHQ<sub>sed</sub>) identified a hazard level increasing from ‘slight’ at Marnay to ‘moderate’ and ‘major’ at  
1052 Bougival and Triel, respectively (Table 4). This suggests that only Triel was faced with a high level of  
1053 environmental hazard. However, only Bougival was faced with a high (‘major’) hazard level according  
1054 to annual average bioavailability measurements (Table 2), while both downstream stations were  
1055 classified as particularly impacted by biomarker responses (‘major’ and ‘severe’ hazard at Bougival  
1056 and Triel, respectively, based on annual average data; Table 3). The environmental diagnosis of the  
1057 three sites would have been substantially different if based on one or another LOE output, under- or  
1058 over-estimating the environmental risk at each site depending on the LOE. This would also have led to  
1059 contradictory conclusions on the impacts of the Oise River inputs between the two downstream  
1060 stations. These two latter aspects would complexify the decision-making process for environmental

1061 managers. The solution lies in final WOE integration, which compiles the results from each LOE into  
1062 a global hazard index associated to an integrative hazard class translating the overall environmental  
1063 risk at each site.

1064 As a result, it seems relevant to further analyze the environmental hazard in the studied area, basing  
1065 the diagnosis on various aspects including contamination levels, bioavailability, and biological  
1066 responses. Although the biological effects recorded in the present study can be considered as quite  
1067 limited in comparison to contamination levels, remobilization of contaminants (especially those  
1068 trapped in sediment) and/or variations of some controlling factors (*e.g.*, temperature, flow rates, or  
1069 physico-chemistry of the surrounding environment) would result in a strong increase in bioavailable  
1070 contamination levels, and this in turn could induce more severe biological impacts.

1071 To avoid such critical situations for the health of aquatic ecosystems, efforts should focus on  
1072 decontamination and remediation procedures in the most impacted sites (Bougival and Triel) before  
1073 more adverse effects occur at the population level, as suggested by some biological responses  
1074 evidenced in the present study (*e.g.*, acute toxicity, altered microbial communities, reproductive  
1075 impairments etc.).

1076

### 1077 *3.6. Bacterial communities*

1078 The bacterial community composition of the water column was studied using high throughput  
1079 sequencing of bacterial 16S-rRNA genes during three sampling campaigns (C1, C3, and C4).  
1080 Unfortunately, due to a technical problem, the data from the Triel sampling station were not available  
1081 for the winter campaign (C4). The dissimilarity in bacterial community structure (number and relative  
1082 abundance of different OTU<sub>0.03</sub>) among the different samples are presented as a three-dimension  
1083 NMDS graph (Fig. 7). This figure clearly shows that samples from Marnay were grouped together,  
1084 while obviously separated from the Bougival and Triel samples that were close (except for the  
1085 December 2012 Bougival sample). Similar differences were previously observed on ARISA  
1086 (Automated Ribosomal Intergenic Spacer Analysis) profiles of river biofilms collected from the same  
1087 sampling sites (Fechner et al. 2012). This suggests that the bacterial communities of the water samples  
1088 collected upstream of Paris were different from those sampled downstream. These observations on  
1089 bacterial communities are also in good agreement with the global hazard assessment illustrated by  
1090 WOE indices, which were the lowest and varied between 15% to 30% for Marnay. In contrast, the  
1091 integrative HQ calculated for the two downstream stations covered the same range of higher values  
1092 (54% to 70%), except for the C4 campaign. For this campaign, WOE indices from Bougival were  
1093 close to the range of values from Marnay; in parallel, bacterial community compositions were similar  
1094 in the two stations during the winter campaign. Globally, this study shows that responses at the

1095 bacterial community level reflect the global disturbance of the environment particularly well. Results  
1096 from river biofilms collected during the same campaigns also corroborate this observation (Faburé et  
1097 al. 2015). The use of microbial communities in an ERA context might be very powerful in the future;  
1098 however the conclusions from such an approach (*i.e.*, the classification of sites in relation to one  
1099 another) can only be relative since they are drawn from inter-site qualitative comparisons, as reference  
1100 levels are nowadays still lacking.

1101

## 1102 **4. Conclusion**

1103 The WOE approach applied in the present study proved efficient and relevant in terms of both global  
1104 environmental hazard diagnosis and seasonality analysis. The procedure was particularly improved  
1105 using external reference levels integrating natural variations of responses and confounding factors,  
1106 especially in LOEs#2 and #3. This improved the reliability of WOE integration results, which better  
1107 reflected the level of disturbance of organisms at each sampling time, without any interference related  
1108 to acclimation or adaptation mechanisms likely to occur in chronically exposed populations. The  
1109 establishment of reference values and thresholds from numerous studies conducted at the national  
1110 scale also eliminated the need for a reference site in the study area, which could be very problematic in  
1111 large rivers subjected to multiple and diffuse pressures. Our results reveal that at the upstream site,  
1112 generally used as a relative reference or control site in previous investigations in the area, the low  
1113 contamination levels nonetheless resulted in low but significant biological effects.

1114 This approach should be pursued and further developed at larger spatial scales. Bioaccumulation and  
1115 biological responses to pollutants as well as baseline levels may be modulated and altered by long-  
1116 term variations and trends in some key endpoints, *e.g.*, growth and reproduction, themselves governed  
1117 by global factors and large-scale processes (*e.g.*, climate trends and changes, oceanographic cycles,  
1118 etc.) (Garmendia et al. 2015). The in-depth characterization of the baseline levels and relevant effect  
1119 thresholds for such environmentally relevant endpoints is thus a challenge to ensure their relevance  
1120 within ERA purposes.

1121 Another strength of the present work lies in the use of gammarids from the same population for  
1122 bioaccumulation measurements and biomarker analyses. A direct and strong connection was thus  
1123 established between bioaccumulation levels and biological responses, strengthening the conclusions  
1124 from the LOEs based on these data. Moreover, the use of these amphipods is entirely appropriate and  
1125 relevant in the context of ecological/ecotoxicological field studies. Gammarids are widespread in  
1126 European freshwaters, and are key actors in the functioning of these ecosystems as litter degraders and  
1127 as a food source for fish and amphibian species. As a result, multiple biomarkers and bioassays using  
1128 gammarids are available for field-testing of contaminant impacts. Moreover, modelling developments

1129 quantifying the natural variability of these markers in relation to abiotic factors enhance the reliability  
1130 of the *in situ* methodology and allow for its implementation at large spatial and temporal scales in  
1131 monitoring programs (Coulaud et al. 2011; Chaumot et al. 2015).

1132 The assessment of environmental quality was also improved by integrating water column and  
1133 sediment analyses. In the water column, contamination (according to the selected compounds analyzed  
1134 in this matrix) and toxicity (assessed by bioassays) remained relatively limited, but in the sediment  
1135 variable stocks of pollutants accumulated and locally reached very high levels, with various impacts  
1136 on laboratory-exposed organisms. These compounds are likely (at least partially) involved in some of  
1137 the biological responses detected in gammarids through biomarker analyses, since they were  
1138 significantly accumulated by exposed gammarids. This also proves that although we did not trace all  
1139 contaminants in the water, a fraction of these contaminants is bioavailable to organisms through the  
1140 water column. Overall observations suggest that a non-negligible ecological risk in the area could  
1141 threaten benthic biota as well as pelagic organisms through the release and/or remobilization of the  
1142 sediment-bound chemicals into the water column.

1143 Other investigations were performed within the framework of the PIREN-Seine program (*e.g.*,  
1144 bacterial community analyses, bioaccumulation of metal and organic compounds, metal tolerance  
1145 acquisition in biofilms), but were not integrated into the WOE model because reference levels and  
1146 thresholds still remain difficult to set. However, it should be mentioned that these approaches gave  
1147 similar results, clearly differentiating the upstream (Marnay) station from the downstream (Bougival  
1148 and Triel) sites, in relation to the contamination gradient. There is no doubt that these experiments  
1149 have to be further developed, but even in their current state they can be valuable tools with successful  
1150 *in situ* deployment in a biomonitoring context, and it would be relevant to integrate them into an ERA  
1151 procedure as they provide information at the community level.

1152 Finally, the WOE approach applied in the present study was based on the integration of each response  
1153 into a global hazard index in a similar way, including pseudo normalization of the data. Thus the  
1154 results from various sampling times remained comparable and were reported on a common grid of  
1155 hazard classification. Such a procedure represents an advantageous and practical tool in the diagnosis  
1156 of environmental hazard because it yields relevant information classifying the most problematic  
1157 substances and effects, and gradually identifies the most impacted sites (comparing HQ values) with  
1158 an associated hazard level. The most remarkable strong point of the approach lies in the ability of the  
1159 model to integrate a large amount of endpoints characterizing various aspects of the environmental  
1160 risk and to generate very 'simple' and 'comprehensible' integrative outputs from this large dataset,  
1161 *i.e.*, the WOE index and the relative hazard class.

1162 This WOE model may be very helpful for environment managers in decision-making processes to plan  
1163 remediation procedures and/or actions to reduce emissions and/or uses of problematic substances.

1164 Combined with the available biomonitoring tools used in the present study, this approach could also be  
1165 implemented on a long-term basis to monitor the potential improvement of environmental quality  
1166 following environmental management measures.

1167

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1396 **Figure captions**

1397 **Fig. 1** Map of the three sampling stations (Marnay, Bougival, and Triel) along the Seine River (in the  
1398 north of France) adapted from Faburé et al. (2015). Arrows indicate the water flow direction. The city  
1399 of Paris is represented in dark grey, and the densely urbanized area surrounding the French capital is  
1400 colored in light grey. Source (France map): [www.histgeo.ac-aix-marseille.fr](http://www.histgeo.ac-aix-marseille.fr), © Daniel Dalet

1401

1402 **Fig. 2** Contribution of each class of chemicals to ChemHQ<sub>water</sub> values (a), and ChemHQ<sub>sed</sub> values  
1403 using reference values for individual substances (b), or for each class of compounds (c). See Table 1  
1404 footnote for details. PESTs, pesticides; AKPs, alkylphenols, PFAS, perfluoroalkyl substance (PFOS);  
1405 MEs, metal elements; PAHs, polycyclic aromatic hydrocarbons, PCBs, polychlorinated biphenyls;  
1406 PBDEs, polybromodiphenyl ethers; OCPs, organochlorine pesticides; CX, X<sup>th</sup> campaign; AA, annual  
1407 average value (mean of concentrations from the C1 to C4 campaigns)

1408

1409 **Fig. 3** Contribution of each class of chemicals to BioavHQ values (a), and of each class of biomarkers  
1410 to BiomHQ values (b). Only the contributions of chemicals to the annual average (AA) BioavHQ  
1411 values calculated for each sampling site are shown. PAHs, polycyclic aromatic hydrocarbons, PCBs,  
1412 polychlorinated biphenyls; PBDEs, polybromodiphenyl ethers; OCPs, organochlorine pesticides; MEs,  
1413 metal elements. Within LOE#3 (BiomHQ values), neurotoxicity was investigated by assessing AChE  
1414 activity. Energy acquisition markers included cellulase, trypsin, and amylase enzymatic activities.  
1415 Survival was assessed using mortality rates. Feeding rate measurements were used to track feeding  
1416 behavior. Reproduction was studied through molt delay and the number of embryos and oocytes *per*  
1417 female. Please note that reproduction markers and cellulase activity were not investigated in the C4  
1418 campaign. CX, X<sup>th</sup> campaign; AA, annual average value (mean of effects calculated from the C1 to C4  
1419 campaigns); N/A, not applicable (as BiomHQ was equal to 0 for Marnay C4)

1420

1421 **Fig. 4** Contribution of each class of bioassay endpoints to ToxHQ<sub>water</sub> (a) and ToxHQ<sub>sed</sub> (b) values.  
1422 Survival endpoints included embryonic and larval viability (MELA). Development was characterized  
1423 by recording hatching success and time to hatch (MELA). The percentage of abnormal larvae was  
1424 selected to illustrate teratogenicity (MELA). Biometric measurements of larvae at hatching, including  
1425 total body length and head size, were used to evaluate *in ovo* growth (MELA). ER, TR, AR/GR, and  
1426 Anti-AR induction factors were gathered to study endocrine-disrupting potency (ED *in vitro*  
1427 bioassays). Cytotoxicity and genotoxicity potencies of sediment elutriates were evaluated using *in*

1428 *vitro* bioassays, using Microtox and SOS Chromotest procedures, respectively. CX, X<sup>th</sup> campaign;  
1429 AA, annual average value (mean of effects E(i) calculated from the C1 to C4 campaigns)

1430

1431 **Fig. 5** Weight of Evidence indices (WOEs) and associated hazard classes integrating the results of  
1432 each LOE calculated for the three stations during the four sampling campaigns (C1 to C4), and annual  
1433 average (AA) values. The hazard class attributed to each LOE hazard quotient (HQ) is summarized in  
1434 the table below. Please note that in the C2 campaign, only ChemHQ<sub>water</sub> and BioavHQ were evaluated

1435

1436 **Fig. 6** Contribution of each LOE hazard quotient (HQ) to the global WOE values calculated for the  
1437 Marnay (a), Bougival (b), and Triel (c) stations. CX, X<sup>th</sup> campaign; AA, annual average value. Please  
1438 note that as only ChemHQ<sub>water</sub> and BioavHQ were evaluated in the C2 campaign, details on the  
1439 contributions for that campaign are not presented

1440

1441 **Fig. 7** 3D-Non-metric Multi-Dimensional Scaling graphical representation of the dissimilarity  
1442 between bacterial communities of the different samples. Mar, Marnay; Bou, Bougival; Tri, Triel;  
1443 Sept11, C1 campaign; Jul12, C3 campaign; Dec12, C4 campaign

1444



1445 **Supplementary Material captions (ESM\_1.pdf)**

1446

1447 **Supplementary Tables**

1448

1449 **Table S1** List of chemical parameters included into the WOE approach for the water column  
1450 (LOE#1), and associated weightings, CAS numbers and selected reference values

1451

1452 **Table S2** List of chemical parameters included into the WOE approach for the sediment (LOE#1), and  
1453 associated weightings, CAS numbers and selected reference values

1454

1455 **Table S3** List of chemical parameters included into the WOE approach for bioavailability (LOE#2),  
1456 selected reference values and hazard classes attributed to  $RTR_w(i)$  values

1457

1458 **Table S4** Reference values (Ref.) and thresholds (Th(%)) assigned to biomarker responses (LOE#3)  
1459 analyzed in the study

1460

1461 **Table S5** Details of the hazard classes attributed to the effect  $E(i)$  values for biomarker responses  
1462 (LOE#3)

1463

1464 **Table S6** Assigned weightings for the biomarker line of evidence (LOE#3) according to Piva et al.  
1465 (2011)

1466

1467 **Table S7** Reference values (Ref.) and thresholds (Th(%)) assigned to each endpoint for *in vivo*  
1468 (MELA) and *in vitro* (ED, Microtox, SOS Chromotest) bioassays analyzed in the study (LOE#4)

1469

1470 **Table S8** Details of the weighting calculations according to endpoint, matrix and exposure time,  
1471 adapted from Piva et al. (2011)

1472

1473 **Table S9** Concentrations of organic micropollutants and metal elements measured in the water column  
1474 (<0.7 µm) at the three stations during each sampling campaign, and integrated into the Weight-of-  
1475 Evidence approach (LOE#1)

1476

1477 **Table S10** Concentrations of organic micropollutants and metal elements measured in sediment  
1478 (<2 mm) at the three stations during each sampling campaign, and integrated into the Weight-of-  
1479 Evidence approach (LOE#1)

1480

1481 **Table S11** Main physico-chemical characteristics and organic contamination levels in sediments  
1482 sampled along the Seine River

1483

1484 **Table S12** Bioaccumulation levels of organic micropollutants and metal elements measured in  
1485 gammarids at the three stations during each sampling campaign, and integrated into the Weight-of-  
1486 Evidence approach (LOE#2)

1487

1488 **Table S13** Biomarker responses in gammarids at the three stations during each sampling campaign,  
1489 integrated into the Weight-of-Evidence approach (LOE#3)

1490

1491 **Table S14** Bioassay endpoint values observed at the three stations during each sampling campaign,  
1492 and integrated into the Weight-of-Evidence approach (LOE#4)

1493

#### 1494 **Supplementary Figures**

1495

1496 **Fig. S1** Details on the calculation procedure implemented within LOE#1 (sediment and water column  
1497 chemistry), adapted from Piva et al. (2011)

1498

1499 **Fig. S2** Details on the calculation procedure implemented within LOE#2 (bioavailability), adapted  
1500 from Piva et al. (2011)

1501

1502 **Fig. S3** Details on the calculation procedure implemented within LOE#3 (biomarkers), adapted from  
1503 Piva et al. (2011)

1504

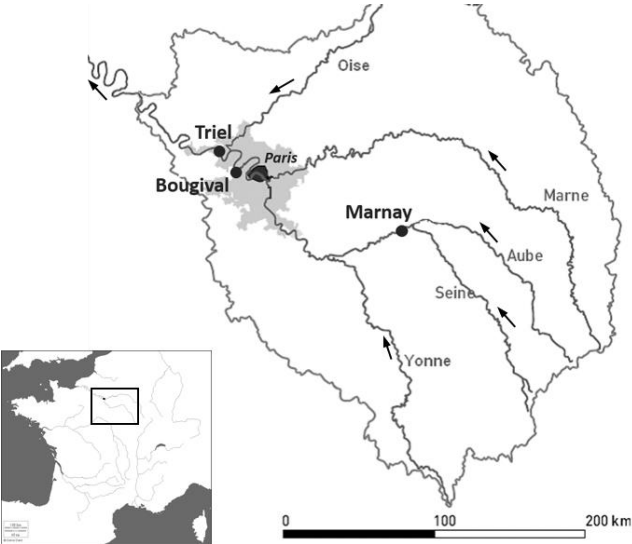
1505 **Fig. S4** Details on the calculation procedure implemented within LOE#4 (bioassays), adapted from  
1506 Piva et al. (2011)

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1508 **Fig. S5** Details on the calculation procedure implemented within WOE integration, adapted from Piva  
1509 et al. (2011)

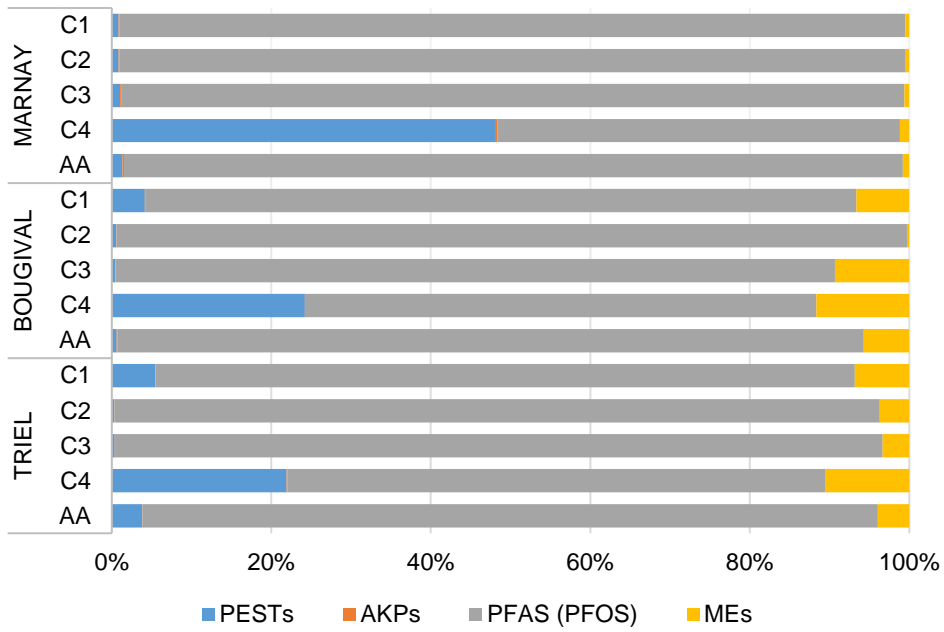
# Figures

Fig. 1

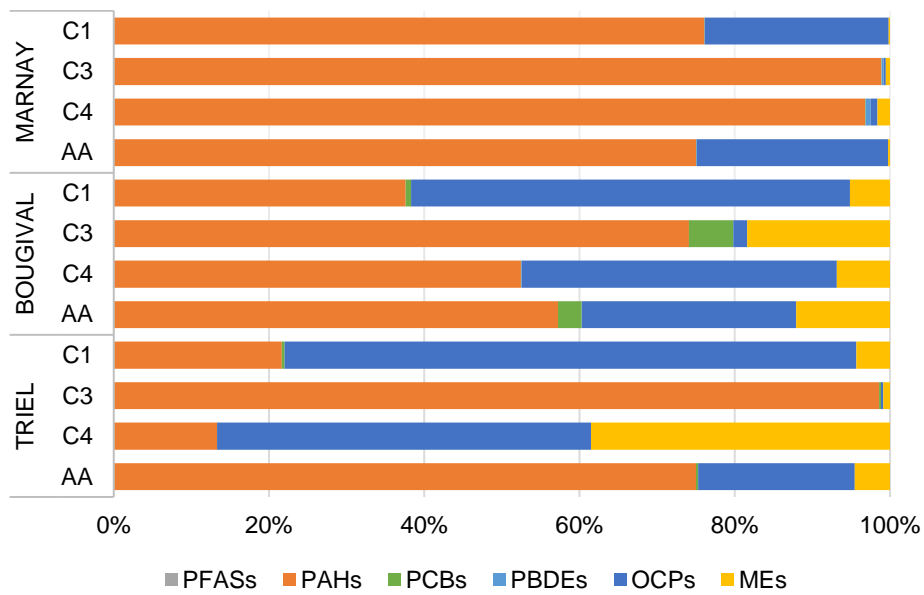


**Fig. 2**

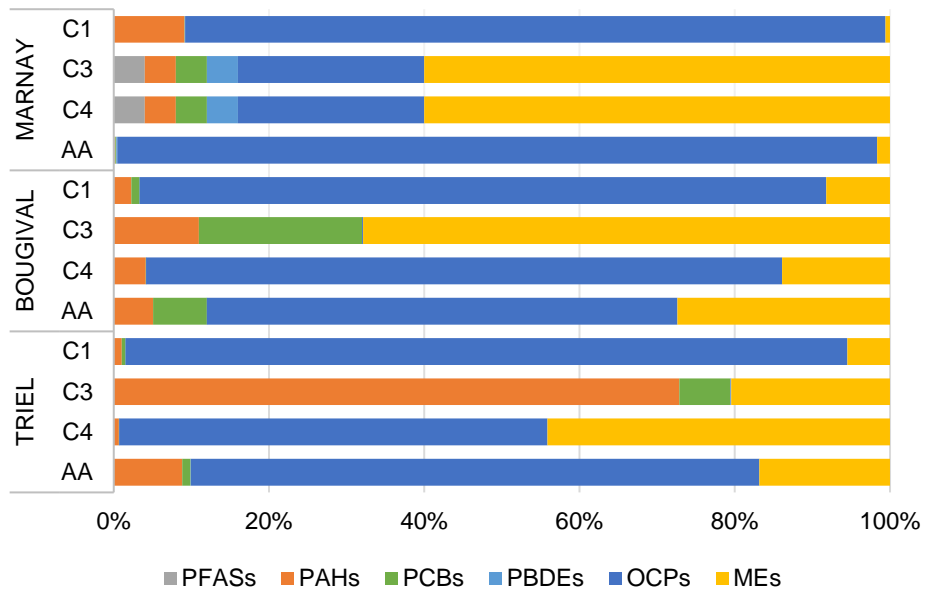
**(a)**



**(b)**

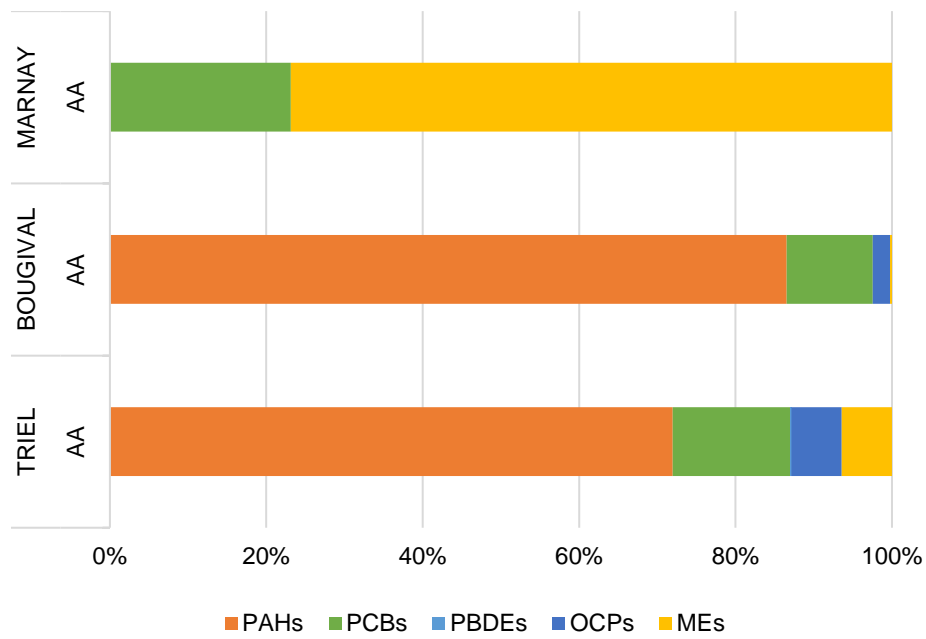


(c)

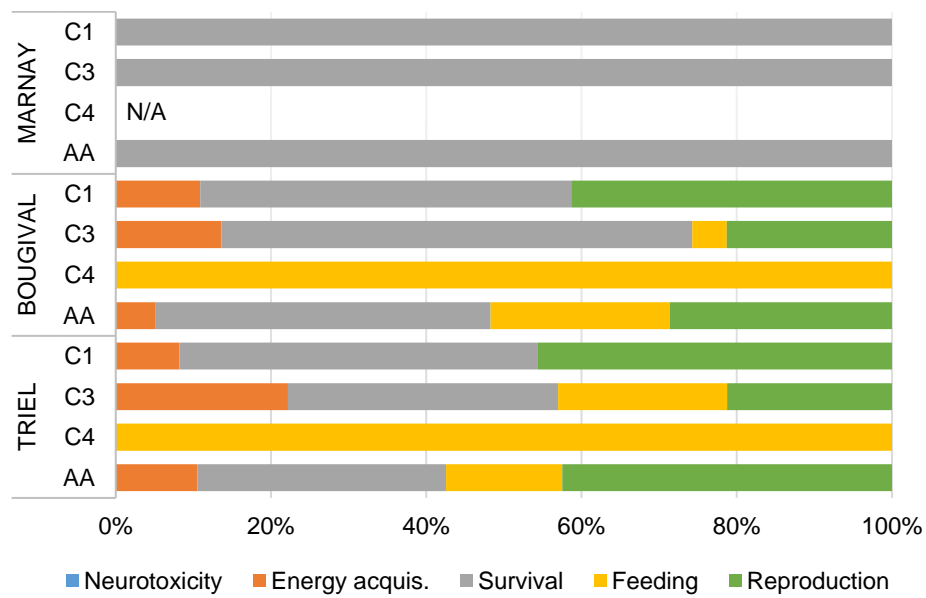


**Fig. 3**

**(a)**

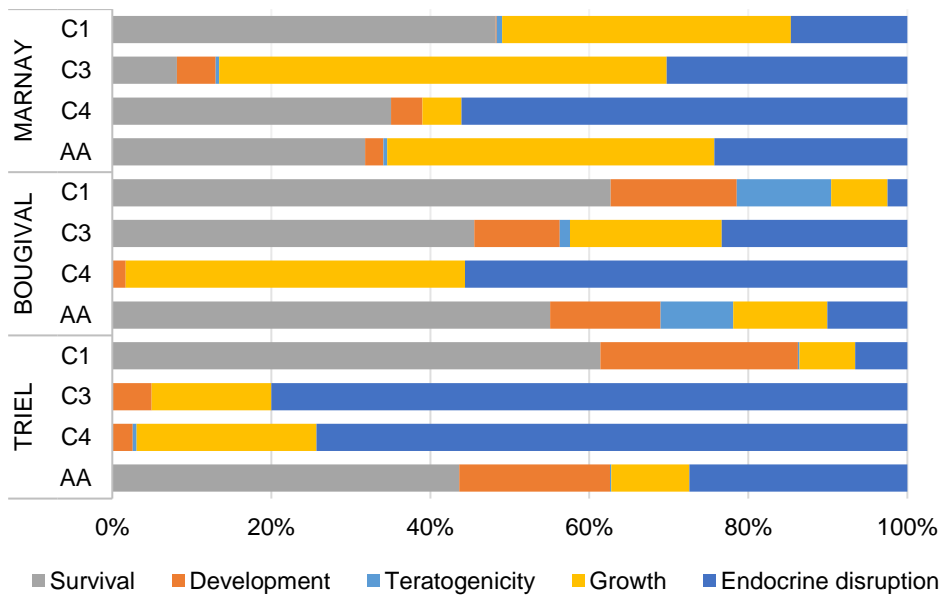


**(b)**



**Fig. 4**

**(a)**



**(b)**

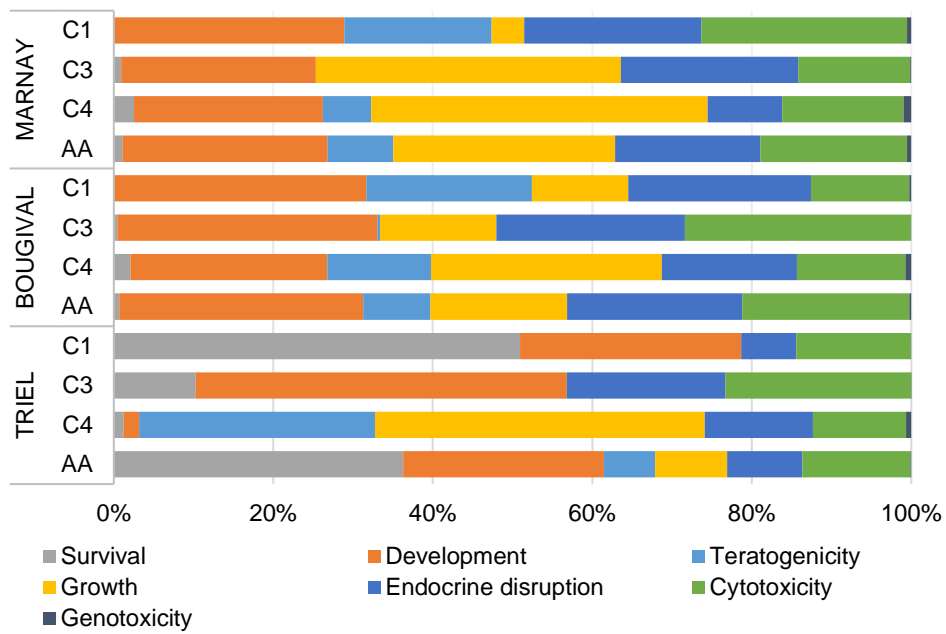
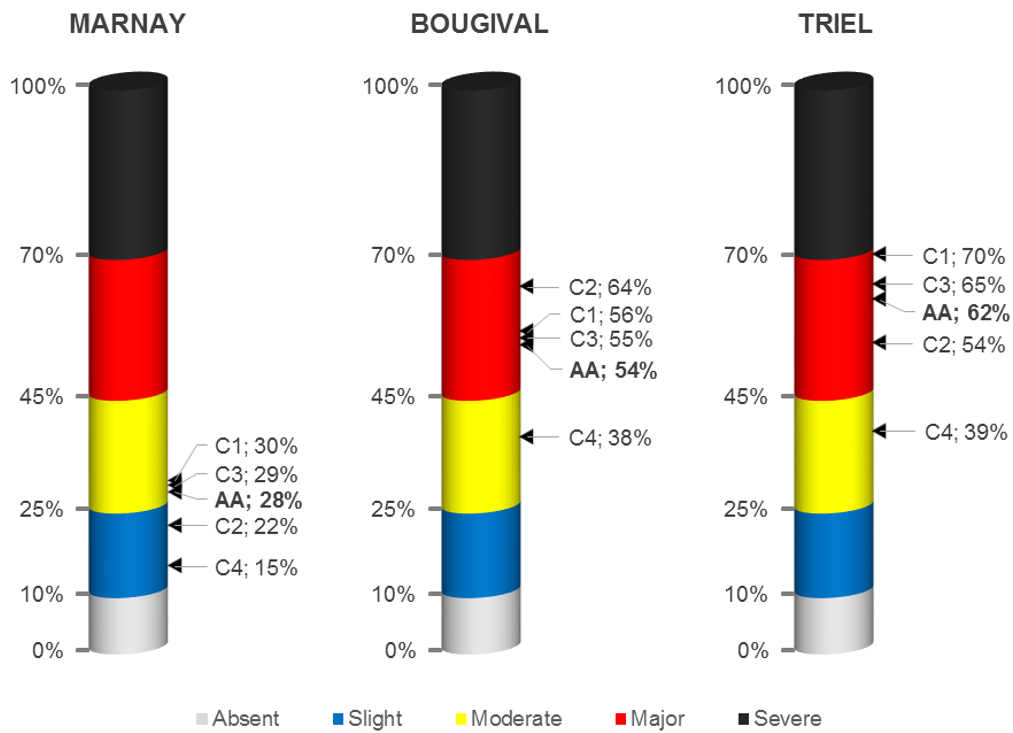




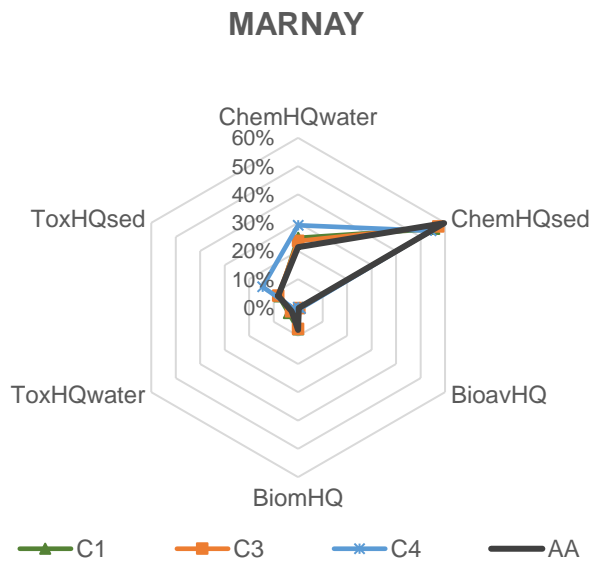
Fig. 5



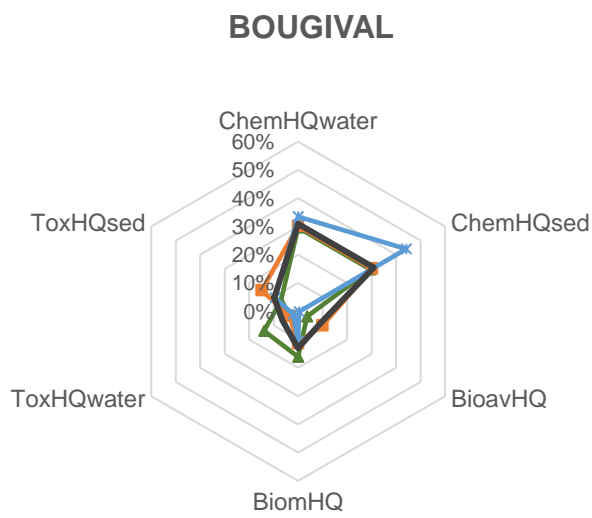
Summary of the hazard classes attributed to the HQs values within each LOE																
HQs	MAR_C1	MAR_C2	MAR_C3	MAR_C4	MAR_AA	BOU_C1	BOU_C2	BOU_C3	BOU_C4	BOU_AA	TRI_C1	TRI_C2	TRI_C3	TRI_C4	TRI_AA	
ChemHQ <sub>water</sub>	Moderate	Moderate	Moderate	Moderate	Moderate	Severe	Severe	Severe	Major	Severe	Severe	Severe	Severe	Major	Severe	
ChemHQ <sub>sec</sub>	Severe	N/A	Severe	Moderate	Severe	Severe	N/A	Severe	Severe	Severe	Severe	N/A	Severe	Severe	Severe	
BioavHQ	Slight	Slight	Slight	Slight	Slight	Major	Major	Major	Slight	Major	Major	Moderate	Moderate	Slight	Moderate	
BiomHQ	Moderate	N/A	Moderate	Slight	Moderate	Severe	N/A	Major	Major	Major	Severe	N/A	Severe	Major	Severe	
ToxHQ <sub>water</sub>	Absent	N/A	Absent	Absent	Absent	Moderate	N/A	Absent	Absent	Slight	Major	N/A	Slight	Absent	Slight	
ToxHQ <sub>sec</sub>	Slight	N/A	Slight	Slight	Slight	Slight	N/A	Moderate	Slight	Moderate	Severe	N/A	Severe	Slight	Major	

**Fig. 6**

**(a)**



**(b)**



(c)

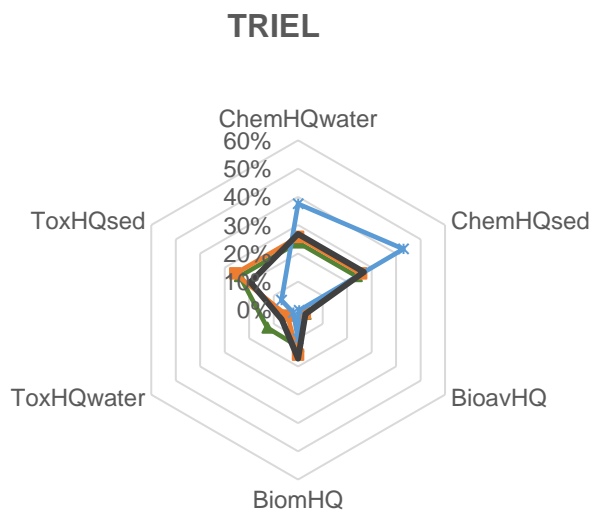
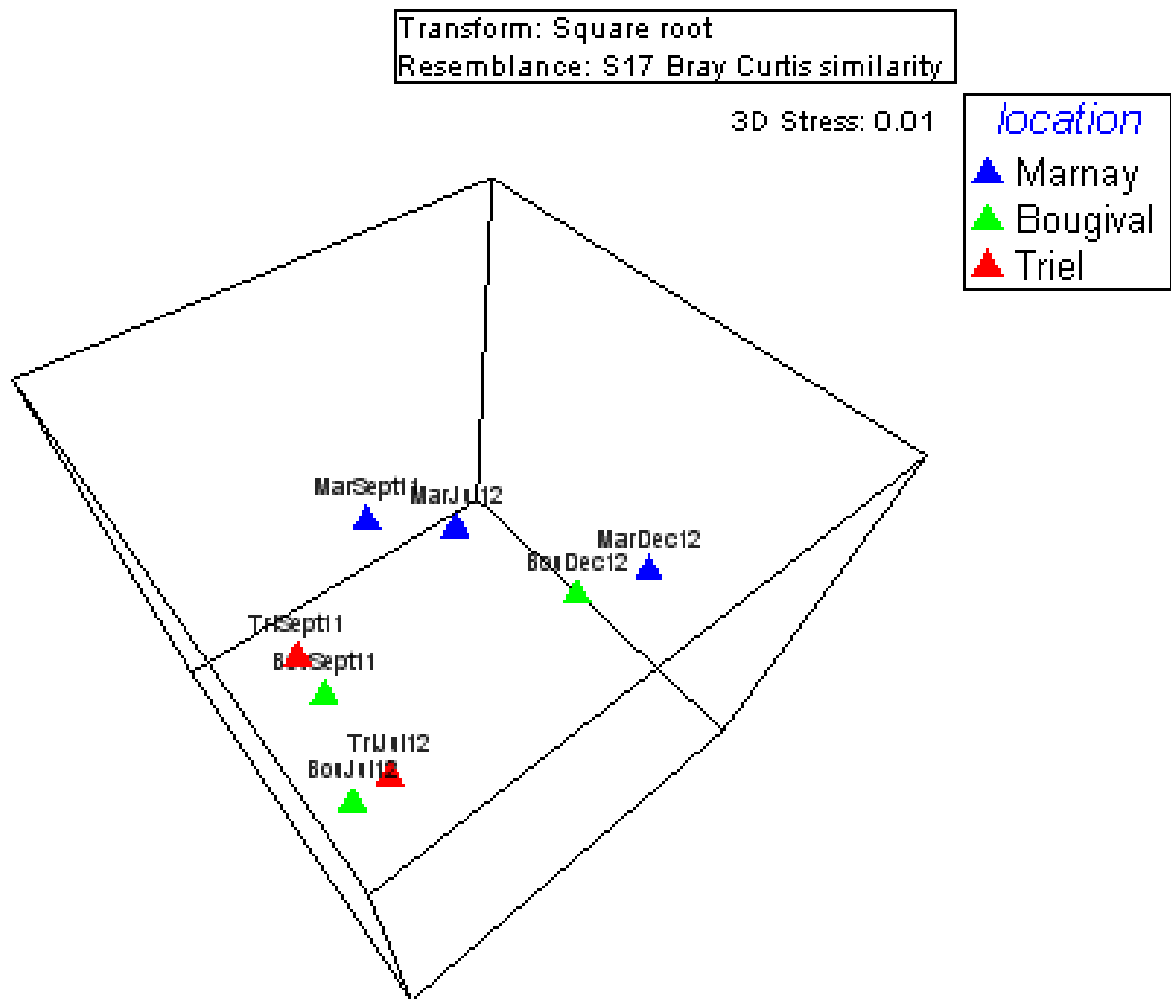


Fig. 7



**Table 1** Chemical Hazard Quotients calculated for the water column (ChemHQ<sub>water</sub>) and for sediments (ChemHQ<sub>sed</sub>)

	Water column		Sediment			
	ChemHQ <sub>water</sub>	Hazard class	ChemHQ <sub>sed</sub> <sup>a</sup>	Hazard class	ChemHQ <sub>sed</sub> <sup>b</sup>	Hazard class
MAR_C1	5.8	Moderate	92.6	Severe	24.3	Severe
MAR_C2	5.6	Moderate	N/A	N/A	N/A	N/A
MAR_C3	5.3	Moderate	17.1	Severe	0.3	Absent
MAR_C4	3.4	Moderate	6.2	Moderate	0.3	Absent
MAR_AA	4.7	Moderate	41.2	Severe	10.4	Major
BOU_C1	33.3	Severe	318	Severe	200	Severe
BOU_C2	14.9	Severe	N/A	N/A	N/A	N/A
BOU_C3	25.1	Severe	427	Severe	116	Severe
BOU_C4	9.9	Major	150	Severe	74.3	Severe
BOU_AA	19.6	Severe	301	Severe	133	Severe
TRI_C1	52.2	Severe	866	Severe	681	Severe
TRI_C2	29.1	Severe	N/A	N/A	N/A	N/A
TRI_C3	32.2	Severe	2,756	Severe	117	Severe
TRI_C4	11.3	Major	296	Severe	258	Severe
TRI_AA	30.5	Severe	1,309	Severe	355	Severe

a, Hazard quotient calculated using reference value (and measured concentration) for individual substance when available (excepted for ΣPBCs, ΣDDT, ΣDDE and ΣDDD; see ESM Table S2 for definition)

b, Hazard quotient calculated using reference value (and measured concentration) for a class of substances when available (for ΣDDTs, ΣPBDEs and ΣPAHs; see ESM Table S2 for definition)

N/A, not applicable; MAR, Marnay; BOU, Bougival; TRI, Triel, CX, X<sup>th</sup> campaign; AA, annual average (mean of concentrations for C1 to C4 campaigns) value

**Table 2** Bioavailability Hazard Quotients (BioavHQs) calculated using bioaccumulation levels in *Gammarus fossarum* following a 7 days-*in situ* exposure

	<b>BioavHQ</b>	<b>Hazard class index<sup>a</sup></b>	<b>Hazard class</b>
MAR_C1	5.8	147%	Slight
MAR_C2	6.0	135%	Slight
MAR_C3	13.4	165%	Slight
MAR_C4	1.8	150%	Slight
MAR_AA	6.5	129%	Slight
BOU_C1	58.6	924%	Major
BOU_C2	189	2006%	Major
BOU_C3	262	2300%	Major
BOU_C4	1.8	150%	Slight
BOU_AA	233	2012%	Major
TRI_C1	66.0	924%	Major
TRI_C2	64.7	665%	Moderate
TRI_C3	75.7	788%	Moderate
TRI_C4	1.8	150%	Slight
TRI_AA	77.4	829%	Moderate

a, Index used to attribute the hazard class (see Section 2.7.2 for details on calculation).

MAR, Marnay; BOU, Bougival; TRI, Triel, CX, X<sup>th</sup> campaign; AA, annual average (mean of the measurements for C1 to C4 campaigns) value

**Table 3** Biomarker Hazard Quotients (BiomHQs) calculated using biomarker responses in *Gammarus fossarum* following *in situ* exposure along the Seine River

	<b>BiomHQ</b>	<b>Hazard class index<sup>a</sup></b>	<b>Hazard class</b>
MAR_C1	26.4	154%	Moderate
MAR_C3	9.3	151%	Moderate
MAR_C4	0.0	70%	Slight
MAR_AA	11.9	151%	Moderate
BOU_C1	37.4	401%	Severe
BOU_C3	17.8	298%	Major
BOU_C4	12.5	216%	Major
BOU_AA	22.2	327%	Major
TRI_C1	51.2	401%	Severe
TRI_C3	26.9	446%	Severe
TRI_C4	9.4	216%	Major
TRI_AA	34.2	460%	Severe

a, Index used to attribute the hazard class (see Section 2.7.3 for details on calculation).

MAR, Marnay; BOU, Bougival; TRI, Triel, CX, X<sup>th</sup> campaign; AA, annual average (estimated from the mean of the effects E(i) calculated for C1 to C4 campaigns) value

**Table 4** Bioassay Hazard Quotients calculated for the water column (ToxHQ<sub>water</sub>) and for sediment (ToxHQ<sub>sed</sub>)

	Water column			Sediment		
	ToxHQ <sub>water</sub>	Hazard class index <sup>a</sup>	Hazard class	ToxHQ <sub>sed</sub>	Hazard class index <sup>a</sup>	Hazard class
MAR_C1	4.8	0.6	Absent	16.2	1.1	Slight
MAR_C3	3.4	0.4	Absent	16.5	1.1	Slight
MAR_C4	0.8	0.1	Absent	14.9	1.0	Slight
MAR_AA	3.0	0.3	Absent	15.9	1.1	Slight
BOU_C1	32.7	3.8	Moderate	28.9	1.9	Slight
BOU_C3	7.8	0.9	Absent	57.6	3.9	Moderate
BOU_C4	3.2	0.4	Absent	25.0	1.7	Slight
BOU_AA	14.5	1.7	Slight	37.2	2.5	Moderate
TRI_C1	36.5	4.2	Major	113	10	Severe
TRI_C3	11.6	1.3	Slight	68.6	8.5	Severe
TRI_C4	3.2	0.4	Absent	18.2	1.3	Slight
TRI_AA	17.1	2.0	Slight	84.1	5.8	Major

a, index used to attribute the hazard class (see Section 2.7.4 for details on calculation).

MAR, Marnay; BOU, Bougival; TRI, Triel, CX, X<sup>th</sup> campaign; AA, annual average (estimated from the mean of the effects E(i) calculated for C1 to C4 campaigns) value