Scale-dependency of macroinvertebrates communities responses to contaminated sediments within run-of-river dams

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Summary

Thanks to their nutrient recycling function and their importance in food-webs, macroinvertebrates are crucial to the functioning of aquatic ecosystems. Because it constitutes an essential compartment for biodiversity and functioning of aquatic ecosystem, but also a potential source of contamination, sediment is an important habitat to monitor and evaluate. In this context, we focused on macroinvertebrates communities within run-of-river dams, that are privileged areas for sediment and pollutants accumulation. Little is known about organization and response of littoral macroinvertebrates communities within run-of-river dam, so we aimed to evaluate (i) their functional and structural composition and (ii) the impact of pollutants accumulation on them to select the most efficient scales and tools for the biomonitoring of the contaminated sediments . Two run-of-river dams located in French alpine area were selected and three spatial scales were examined : transversal (banks and channel), transversal x longitudinal (banks/channel x tail/middle/dam) and patch scale (erosion and sedimentation habitats). At the patch scale, we evidenced that the heterogeneity of littoral habitats provides many available niches, that allow the development of diversified macroinvertebrates communities and thus highly variable responses to contamination. However, littoral habitats, once pooled in the global "banks" spatial scale, spotlight the effects of toxic disturbance .

Keys words : Contaminated sediment; Scale-dependancy; Invertebrates; Run-of-river dams; Functional traits

1. Introduction

1.1 Research context

If we consider that only 0.014% of Earth's Water occurs in the biosphere, water is a limiting resource (Gleick, 1993). Increasing need of water resource for human populations, agriculture and energy production has induced an excessive development of dams or weirs and thus, many hydromorphological or chemical disturbances of river systems (Zwick, 1992; Ward and Stanford, 1995; Bredenhand and Samways, 2009). Owing to dam presence, the disruption of river continuity (Stanford et al., 1996; Poff et al., 1997; Born et al., 1998) limits sediment transport which accumulates within storages. This accumulated sediment becomes sink and source of historic contamination. In fact, sediments have a strong pollutants adsorption capacity (Cairns et al., 1984; Chapman et al., 1990; Estebe et al., 1997), with contamination levels often greater than in the whole water column (Chapman, 1992). Moreover, when disturbed and resuspended, sediments can release adsorbed contaminants into the water-column, that will be dispersed within the run-of-river dam and in downstream ecosystems. In this context, historical contamination is a real threat to the ecological integrity of many aquatic systems (Sheppard, 2005; Norris et al., 2007; Johnston and Roberts, 2009).

1.2 Biomonitoring of contaminated sediment

Contaminants stocked in the sediments exert a persistent pressure which implies chronic and sublethal responses, with the alteration of macroinvertebrates communities for instance (Field and Pitt, 1990; Beyer et al., 2000; Viganò et al., 2002). However, the effects of those contaminants may extend beyond sediment habitats, with their transfer to other compartments (Larsson, 1985; Asare et al., 2000; Coulthard and Macklin, 2003). For all these reasons, biomonitoring tools were developed for contaminated sediment. Evaluation of sediments toxicity is essentially completed by biotests in laboratories but rarely account for responses at the community level (Lafont et al., 2007). However, because contamination can induce modifications in ecosystem's processes and thus, affect its integrity (Kiffney and Clements, 1994), it's necessary to focus on community's and ecosystem's levels. Thus, triadic studies that combine chemical, ecotoxicological and ecological approaches to evaluate sediment toxicity appear to be more appropriate tools, while still neglecting ecosystem functioning (Long and Chapman, 1985; Borgmann et al., 2001; Sorensen et al., 2007). Despite these challenges associated with sediment biomonitoring, storages, which are principally concerned by this topic, are rarely studied, partly because they are not considered within legal texts. This is particularly surprising, knowing that 60 000 dams are referenced in France. Since there is few knowledge of contaminated sediments' effects on macroinvertebrates communities (Ramsey et al., 2005), understanding the constraints on community structure and functionning in run-of-river dams is now an important challenge.

In this context, we aimed to assess structural and bio-ecological responses to contamination across several spatial scales, through different ecological indicators. We hypothesized that: (i) invertebrates communities should respond functionnally and structurally to contaminated sediment but we forecast multiple responses according to the different spatial scales and (ii) when contamination is low, community response to pollutants should be overcomed by habitat heterogeneity.

2. Material and methods

2.1 Sampling design

Study area and contamination status

Two run-of-river dams of a French alpine river (the name of the river will not be quoted because of the confidentiality agreements with the hydroelectric company exploiting the dams) were selected in order to examine macroinvertebrates composition associated with sediments' contamination. The catchment area is dominantly industrial and urbanized inducing an accumulation of metallic pollutants in the sediment of two successive hydroelectric dams. PCB and most of PAH being below detection limits, the organic contamination is low. Physicochemical parameters such as the concentration of dissolved oxygen, the temperature and conductivity were also measured (Table 1). The data evidenced different level of metallic contamination between the two systems.

Macroinvertebrates sampling

Macroinvertebrates were sampled in May 2008 with an original sampling protocol. To distinguish influences of the different hydraulic and hydro-morphological conditions, storages associated to run-of-river dams were subdivided in three areas called "tail", "middle" and "dam". The tail is closer to river conditions, the dam is typical of a lentic system and the middle exhibits intermediate characteristics. Similarly, communities of the banks and of the channel were sampled separately. Habitat's description was performed on each bank before sampling macroinvertebrates communities with a surber net (mesh size 500 µm, sampled area $0.05 m^2$).For the channel, the macroinvertebrates were sampled by dredging from a boat perpendicularly to one transect for each of the three areas defined above. For each transect, the left side, the middle and the left sides of the channel were sampled. The samples were preserved in 4% formalin on the field and the macroinvertebrates were sieved and sorted out at the laboratory, identified and counted at the genus' level (Tachet et al. 2000) except for Diptera (family and tribe level), Oligochaeta, and Nematoda.

2.2 Data analysis

Three spatial scales were investigated: a) transversal scale– samples were pooled according to their bank or channel origin – b) transversal x longitudinal scale – samples were pooled according to the two factors considered together, for instance banks x tail – and finally c) patch scale – samples were pooled according to the habitat type (erosion, sedimentation or vegetation). For each scale, data were explored through three types of indicators: structure indices, taxonomic assemblages and bio-ecological traits structure.

Richness, abundance, proportion of main groups (EPT, Diptera, Molluscs, and Crustacean), Shannon and Weaver diversity index, Simpson evenness and Rao functional diversity index (Lavorel et al., 2008; de Bello et al., 2009), were calculated. The functional diversity represents the overall difference among species in a community according to their traits. We applied this index on the distribution of categories within 22 traits (Table 2) describing biological and ecological traits of macroinvertebrates (Usseglio-Polatera et al., 2000). At the transversal scale, differences between run-of-river dams were investigated by a Principal Component Analysis (PCA). At patches scales, the interaction between the two tested parameters (habitat type and contamination status) were also assessed by an

ANOVA (normal distribution and homoscedasticity respected when the two factors are considered), then Student's t-test and Mann-Whitney test were used to identify the intra-factor differences (when factors are considered independently, parametric conditions were not always respected). The vegetation habitat type was not investigated here because the number of sampled substrates was too low in the reference run-of-river dam.

Taxonomic composition and bio-ecological structure were also investigated. For each spatial scale, the taxa's abundances were log-transformed and analyzed by Correspondence Analysis (CA). For the functional structure, the biological and ecological categories of traits were weighted by the log-transformed abundance of each taxon. Therefore, for each trait category, the sum of weighted scores was expressed as relative abundance distribution within a trait (Thioulouse et al., 1997). We analyzed the frequencies of the categories using Fuzzy Correspondence Analysis (FCA). We used R software (R development Core Team, 2008) and the ADE4 library (Chessel et al., 2004) for all statistical analysis.

3. Results

3.1 Selection of relevant spatial scales

To select the most relevant spatial scales, permutation tests were realized on the multivariate analysis performed at the three spatial scales. They test the null model, *i.e.* whether the structure of data is link to a particular factor (here the contamination level) or is only the result of stochastic processes. The results are synthetized in table 3. Statistical analysis reveals that the transversal scale evidences significant faunistic and functional differences between the two stations, while the patch scale discriminates the two stations only on the basis of indices.

Lastly, the transversal x longitudinal scale does not highlight inter-site differences. For these reasons, only results obtained for transversal and patch scales will be detailed below.

3.2 Response of indices on the two selected space scales

Transversal scale

The first axis of the principal component analysis (Fig.1a) realized on index (table 4a) separates the reference banks from channels and disturbed banks. Observing the results of correlations' circle (Fig.1b), this axis is strongly correlated with richness and diversity index. Indeed, even if the banks offer more habitats than the channel, the contaminated banks exhibit twice less species than the reference banks and on average, as many species as in the channel. The same observation can be made with the taxonomic and functional diversities. The EPT (Ephemeroptera, Plecoptera and Trichoptera) and the Molluscs have suffered more from the disturbance. The second axis of the PCA defines an abundance gradient positively correlated with reference channel. Thus reference run-of-river dam is characterized by rich and diversified littoral communities and high abundances in the channel. In contrast, the analysis evidenced impoverished communities within disturbed banks. In spite of marked reduction of abundance, disturbed channel seems less disturbed, the indices being close to those of the reference channel. To some extent, at this level of investigation, channels show structural similarities whereas banks index distinguish both run-of-river dams.

Patches scale

The response of the richness, the abundance, the taxonomic and the functional diversities, depending on two factors (contamination status and habitat type) was tested by an ANOVA. The absence of a significant interaction between the factors (table 5) permits us to test them independently. All variables respond significantly to habitat type (Table 5). Conversely, at patch scale, only richness discriminates toxic contamination status. Indeed, like table 4b shows, the sedimentation habitats on the disturbed station are impoverished, that we can relate to the accumulation of metals in the sediments.

3.3 Taxonomic against bio-ecological structure

Transversal scale

The first axis of the correspondent analysis (Fig.2) shows differences of taxa assemblages between reference and disturbed run-of-river dams. The second axis reveals similarities between banks and channel in the reference system, while differences are evidenced in the disturbed one. According to the fuzzy coding analysis (Fig.3), the relative importance of the two factors (transversal localization and contamination status) is inverted when compared to the taxonomic analysis. Indeed the first axis shows that assemblages are functionally similar in banks and channels in the reference system and different in the contaminated one while the second axis separates the contamination level. Moreover, the percentage of explained variance is higher with fuzzy coding analysis (77 % versus 44 %).

Patches scale

The main factor controlling functional analysis is the habitat type instead of the contamination (Fig.4). The factorial plane F1F2 evidences that differences between samples were governed by the habitat type, with discrimination along the F1 axis. Conversely, within an habitat type, no differences are observed according to the contamination status. In the same way, the analysis of faunistic assemblage doesn't' reveal significant responses. Finally, similarly to indices, at this scale, we show a difference between habitats rather than between contamination status.

4. Discussion

4.1 Spatial scale

Because observation scale governs our ability to detect and explain the contamination impacts on macroinvertebrates communities, it is important to determine which spatial scale, and which indicators (indices, taxonomic, bio-ecological traits) are the most useful and efficient to detect the consequences of contaminated sediments. This step is important to develop relevant tools for the biomonitoring of this compartment.

Transversal scale

Our results showed the ability of banks' communities to identify contamination's effects in contrast to those of channel. At this spatial scale, within-station substrate heterogeneity effects are overcomed by between-station differences associated with contamination levels. Moreover, the habitat constraint is weaker in banks, with a greater niche and macroinvertebrates communities diversity (Heino, 2000; Harrison and Hildrew, 2001). It explains why banks are more prone than channel to differ between sites with various contamination levels. Finally, being located at the land/water interface and playing a key role in ecosystems' processes, the knowledge of the littoral communities' structuration and of their functioning is important. For example, in lakes, this area has been identified as an important hydro-morphological component supporting ecological quality (Naiman and Décamps, 1997; Rowan et al., 2006; Elosegi et al., 2010). Free and colleagues (2009), bring to light the close association of ecotone's integrity with the requirements for adult life stages of mayflies. James (1998) insist on its importance in overall production and in allochthonous carbon contribution to system.

Patches scale

In contrast with river system (Pardo and Armitage, 1997), patch scale wasn’t relevant to discriminate contamination effect. This result could be explained by the extreme variability and complexity of patches communities which reduces the sensibility of impacts detection (Donohue et al., 2009). Our study reveals that the taxonomic and bioecological structures of macroinvertebrates communities were mostly governed by habitat type, while the contamination only influences richness. Since few studies focused on run-of-river dams, we can only compare our results to those obtained in lakes or ponds. However, even in these systems, few studies have focused on the use of littoral habitats for ecological assessment. Even if White and colleagues (2003) recommend to base the sampling strategy on pebble or boulder habitat, our results differed with none significant interaction between habitat type and contamination. However, this could be explained by the analytical strategy, all erosion habitats being pooled. Smaller scale should bring such information.

As Levin (1992) noted, “The key for understanding how information is transferred across scales is to determine what information is preserved and what information is lost from one scale to the other”. We observed that our ability to evidence a response of communities to contaminated sediment depends on the level at which we observe it. Our results suggest that focusing sampling effort on banks is more relevant and practical for the biomonitoring of contaminated sediment.

4.2 Indicators scales

For a long time, only taxonomic response to environmental variables and to the contamination was evaluated with the consensus that the loss of species is associated to a disturbance of the ecosystem. However, changes in the distribution and in abundance of one species can result in disproportionate and unexpected responses of other species resulting from an attempt to compensate functional changes within the community (Naeem, 1998).This suggests that studying spatial scale won't be enough, and that it is also necessary to wonder about relevant indicators to identify and evaluate a perturbation. Indeed, when we use taxonomic or functional indicators, we don’t observe necessary the same response: the loss of species doesn’t systematically imply a response of the functional structure. In fact, species may appear to perform the same function (i.e. be redundant) under a restricted set of conditions, yet their functional roles may vary in naturally heterogeneous environments (Walker, 1992; Wellnitz and Poff, 2001).. Traits are one of the tools developed to investigate functional characteristics of a community. By definition a trait is a surrogate of organism performance and/or individual fitness (Violle et al., 2007). Numerous studies showed the ability of biological and ecological traits to discriminate metallic (Archaimbault et al., 2010), hydraulic (Snook and Milner, 2002; Griswold et al., 2008) or organic (Charvet et al., 1998) perturbations. In the same way, even if we observed responses of taxonomic structure to contamination, our results showed the relevance of bioecological structure which is a better tool to evidence the impact of contamination in run-of-river dam. However, this trait based approach assumes that these biological and ecological parameters (autoecology of species) are relevant indicators of species' functions inside the community. In fact, concept of trait finds all its interest when it refers to functional trait (Chapin et al., 2000). Potentially, the traits defined by Usseglio-Polatera et *al*. (2000) could be considered to be functional traits within ecosystem's communities because their changes could directly affect ecosystem's processes through changes in biotic controls (i.e predation) and indirectly through changes in abiotic controls (i.e availability of limiting resources). For instance species traits related to food resources and habits, habitat use and dispersal capacities could be responses to contamination while driving changes in ecosystem processes. In the same way, life history traits related to demographic parameters (life cycle, fecundity, maximal size and number of generation) could be affected by metallic contamination and thus indirectly alter ecosystem functioning by cascade effects (Zavaleta et al., 2009). Traits used in this article are potential traits because coming from literature, and are used as 'response trait', *i.e.* a measure of how the traits assemblages react to environmental parameters at the community level. This response may or may not be correlated with effects on functional processes, thus it is necessary to discern and to be cautious on the notions of functional response trait and functional effect trait (Lavorel and Garnier, 2002; Violle et al., 2007). Forthcoming studies should also measure ecosystem's processes to compare ecosystem functional response to community traits variation in order to identify whether functional traits of response and/or of effect to contaminated sediment could be defined.

4.3 Ranking impacts

Our results lead us to wonder about the hierarchy of the impacts, *i.e.* whether physical constraints could mask the effects of a moderate toxic contamination. Water flow governs the fundamental nature of streams and rivers (Poff et al., 1997; Hart and Finelli, 1999), so modifications of flow caused by dams alters the structure and function of river ecosystems (Malmqvist and Englund, 1996; Hart et al., 2002). However, there have been few studies that have examined the adverse effects of dams on the physical, chemical and biological characteristics of rivers (Poff and Hart, 2002). Presence of dams implies two perturbation types: 1) a physical disturbance by sediment accumulation and the modification of river flow; 2) a toxic disturbance, by potential pollutants accumulation within the sediments. The study of communities in the run-of-river dams can't dissociate these perturbations. The results obtained for the two studied systems revealed that habitats' characteristics of the channel decrease the differences related to contamination's level between the dams. However, no clear pattern is evidenced, highlighting the need to consider the dams and rivers continuum to discriminate these two sources of community modification.

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Fig.1: Results of Principal Component Analysis performed at the transversal scale on the indices table. (a) factorial plane of two run-of-river dams and ()b correlation circle for the 9 indices. Circle and star represent respectively channel and bank samples. Black symbols are for reference system and white symbols are for disturbed system.

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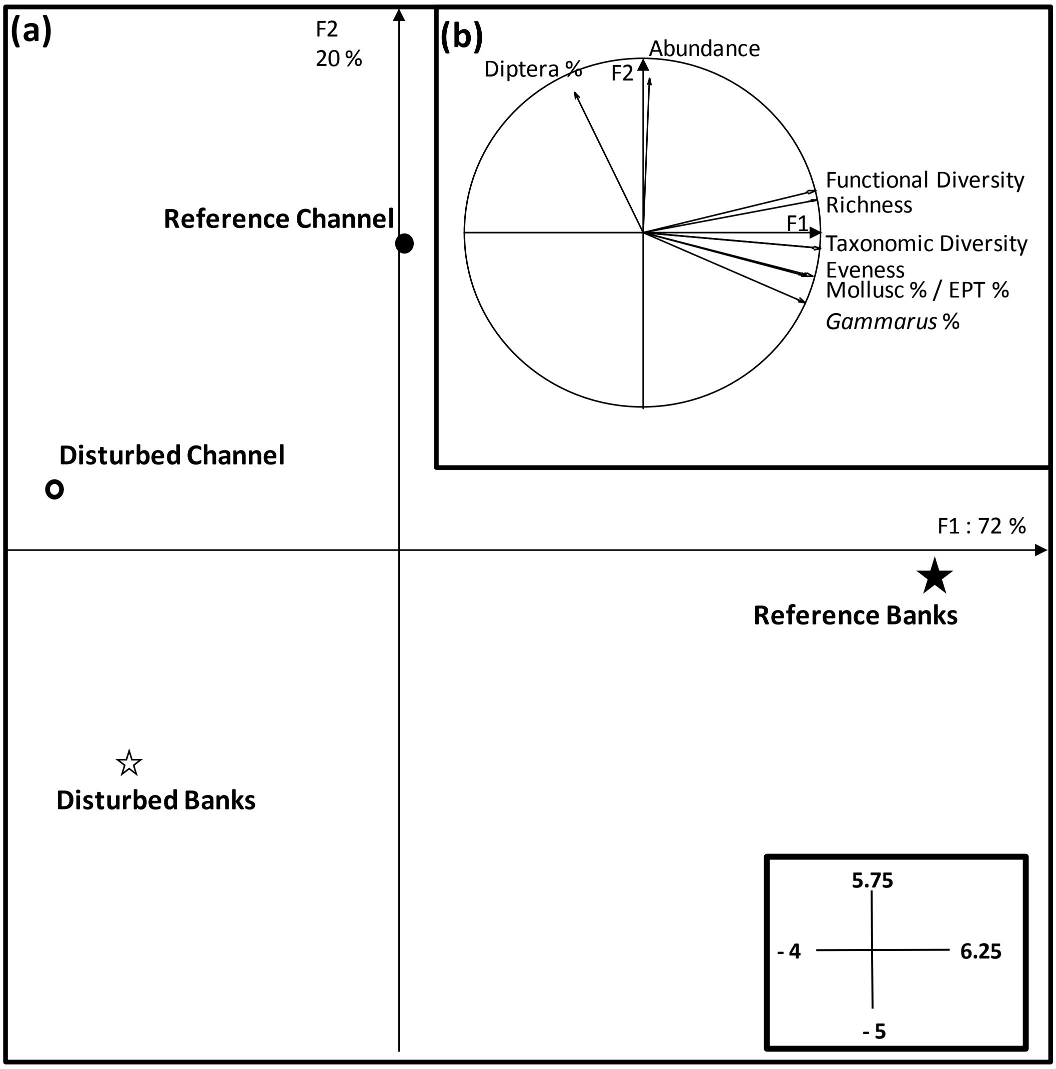
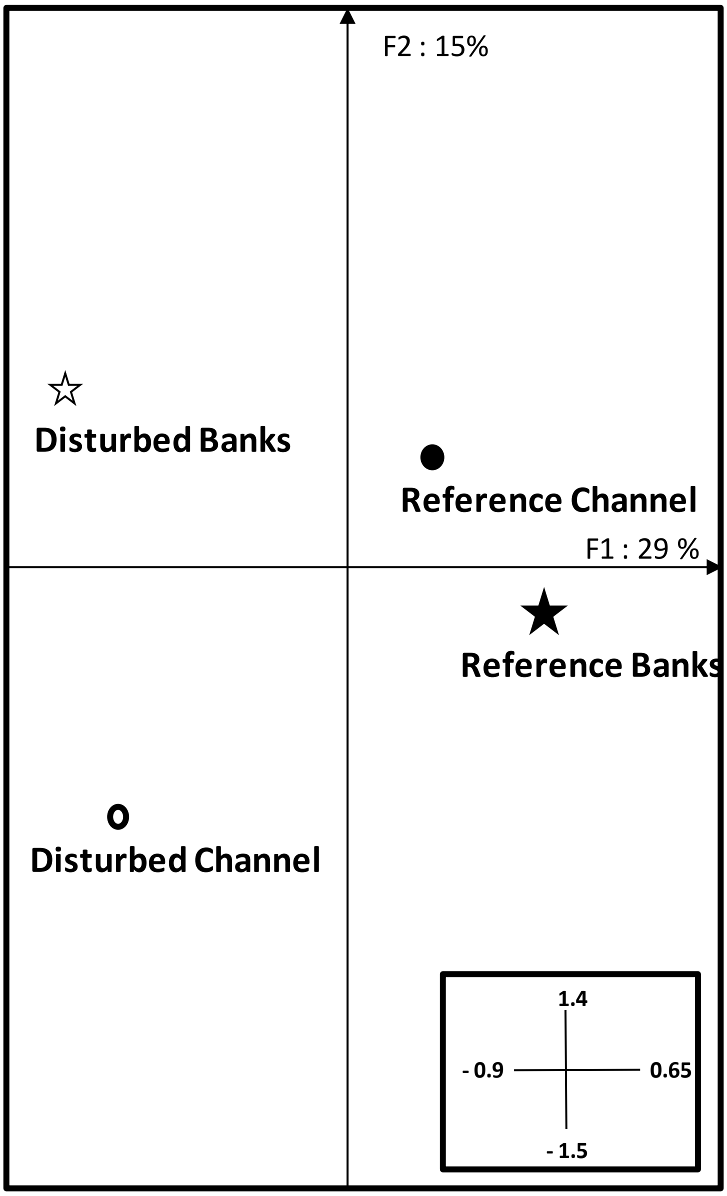
Figure 1



(a)
F2
20 %
Reference Channel
Disturbed Channel
F1 : 72 %
Reference Banks
Disturbed Banks
5.75
- 4
6.25
- 5
(b)
Abundance
Diptera %
F2
Functional Diversity
Richness
F1
Taxonomic Diversity
Eveness
Mollusc % / EPT %
Gammarus %

Figure 2



F2 : 15%
Disturbed Banks
Reference Channel
F1 : 29 %
Reference Banks
Disturbed Channel
1.4
- 0.9
0.65
- 1.5

Figure 3

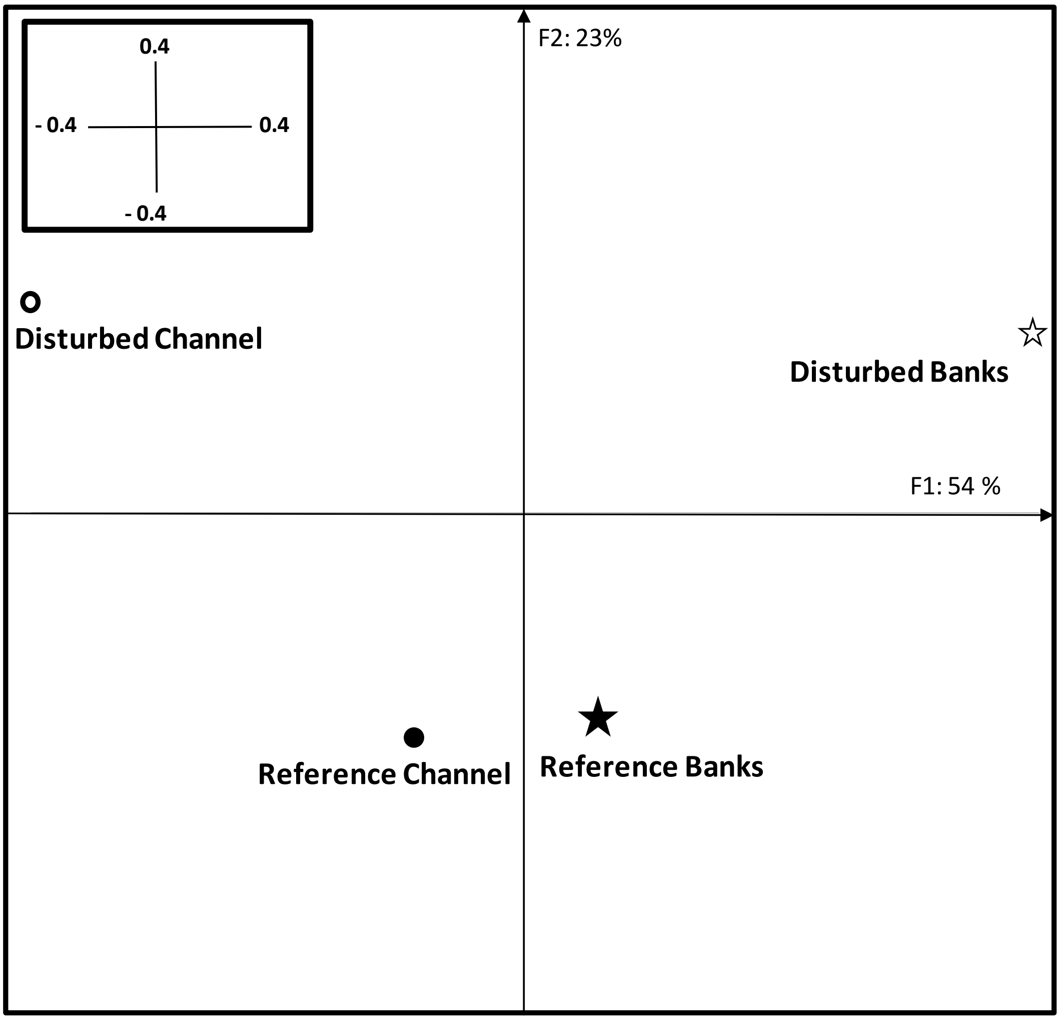

0.4
- 0.4
0.4
- 0.4
F2: 23%
Disturbed Channel
Disturbed Banks
F1: 54 %
Reference Channel
Reference Banks

Figure 4

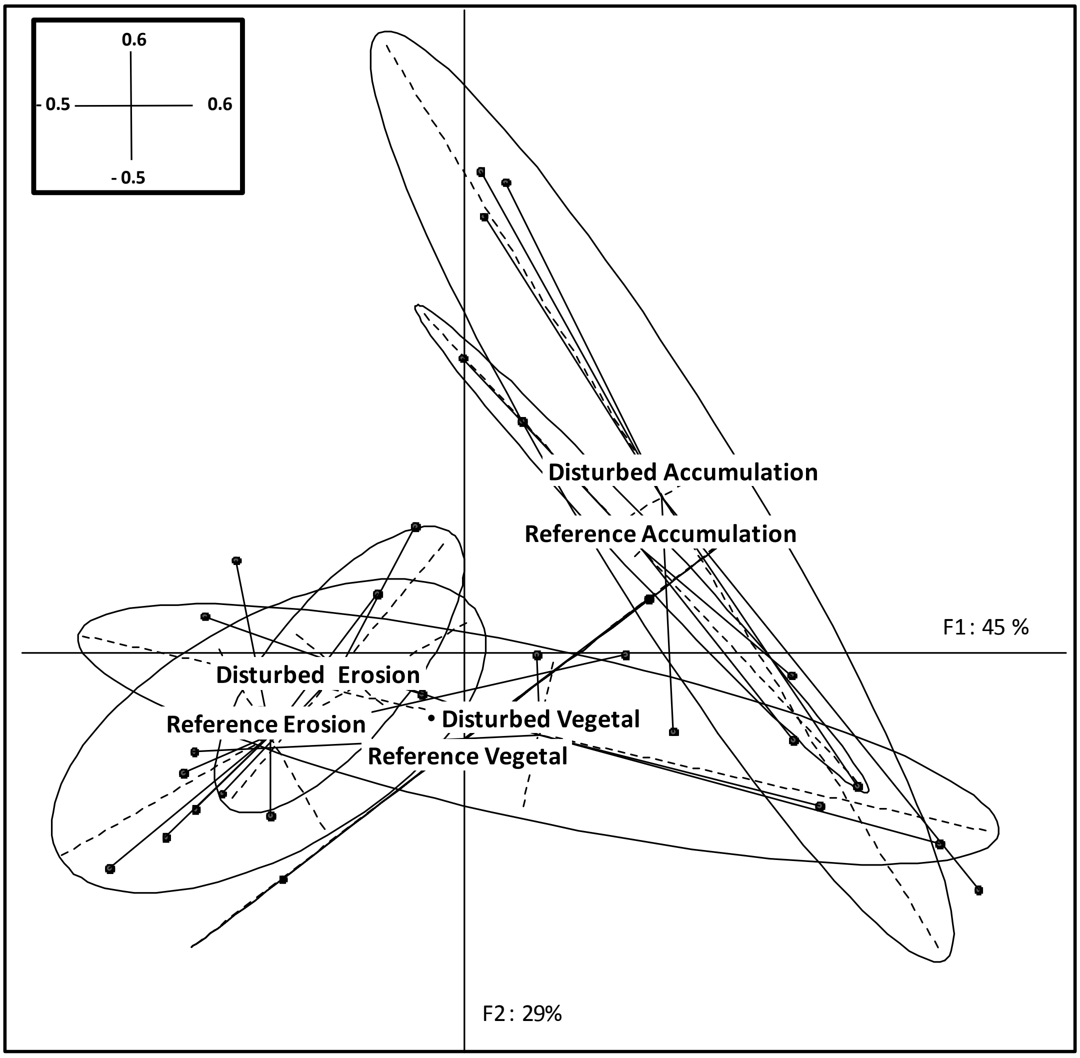

0.6
- 0.5
0.6
- 0.5
Disturbed Accumulation
Reference Accumulation
F1 : 45 %
Disturbed Erosion
Reference Erosion
Disturbed Vegetal
Reference Vegetal
F2 : 29%

Table 1

	Contaminants concentrations in sediments														
	Metals (mg.kgDW-1)										PAH (µg.kgDW-1)				
	Al	Fe	Cr	Co	Cu	Mn	Ni	Pb	Zn	As	BaP	BaA	BgP	Fluo	Ind
Reference site	$9.2*10^3$	$6.5*10^3$	38	4	14	169	7.7	22.5	90	1.9	18	24	27	101	24
Contaminated site	$19.7*10^3$	$15*10^3$	83.5	9	31	423	54.7	17.8	108	1	18	24	27	98	25

	Water chemistry (mg.l^{-1})										
	COD	DBO	Ca	Mg	K	NH4	Cl	NO3	NO2	SO4	PO4	pH
Reference site	1.9	1.5	70	5	2	0.32	15	16	0.28	15	0.218	8.2
Contaminated site	1.8	0.9	68	5	1.7	0.13	13	9.9	0.11	14	0.251	8.15

Table 2

Biological Traits	Categories	Ecological Traits	Categories
Maximal size (cm)	≤ 0.25	Transversal distribution	river channel
	> 0.25 to 0.5		banks, connected side-arms
	> 0.5 to 1		ponds, pools, disconnected side-arms
	> 1 to 2		marshes, peat bogs
	> 2 to 4		temporary waters
	> 4 to 8		lakes
	> 8	Longitudinal distribution	groundwaters
Life span (year)	≤ 1		crenon
	> 1		epirithron
Number of reproductive cycles per year	< 1		metarithron
	1		hyporithron
	> 1		epipotamon
Aquatic stages	egg		metapotamon
	larva		estuary
	nymph		outside river system
	adult	Altitude	lowlands
Reproduction	Ovoviviparity		piedmont level
	Isolated eggs, free		alpine level
	isolated eggs, cemented	Biogeographic area	Pyrenees
	clutches, cemented or fixed		Alps
	clutches, free		Vosges, Jura, Massif Central
	clutches, in vegetation		lowlands (oceanic)
	clutches, terrestrial		lowlands (mediterranean)
	asexual reproduction		flags/boulders/cobbles/pebbles
Dispersal	Aquatic passive	Substrate preferences	gravel
	Aquatic active		sand
	Aerial passive		silt
	Aerial active		macrophytes
Resistance forms	Eggs, statoblasts		microphytes
	Cocoons		twigs/roots
	Housings against desiccation		organic detritus/litter
	Diapause or dormancy		mud
	None	Current velocity	null
Respiration	Tegument		slow (< 25 cm/s)
	Gill		medium (25-50 cm</s)
	Plastron		fast (> 50 cm/s)
	Spiracle	Trophic status	oligotrophic
	Hydrostatic vesicle		mesotrophic
Locomotion	Flier		eutrophic
	Surface swimmer	Salinity (preferences)	freshwater
	Full water swimmer		brackish water
	Crawler	Temperature	Psychrophilic (< 15°C)
	Burrower		Thermophilic (> 15°C)
	Interstitial		Eurythermic
	Temporarily attached	Saprobity	Xenosaprobic
	Permanently attached		Oligosaprobic
Food	Microorganisms		β-Mesosaprobic
	Detritus (< 1mm)		α-Mesosaprobic
	Dead plant (>= 1mm)		Polysaprobic
	Living microphytes	Low pH sensitivity	≤ 4
	Living macrophytes		> 4 to 4.5
	Dead animal (>= 1mm)		> 4.5 to 5
	Living microinvertebrates		> 5 to 5.5
	Living macroinvertebrates		> 5.5 to 6
Feeding habits	Vertebrates		> 6
	Absorber		
	Deposit feeder		
	Shredder		
	Scraper		
	Filter-feeder		
	Piercer		
	Predator		
	Parasite		

Table 3

		Indices	Faunistic assembages	Bioecological traits
Scales	Transversal	p-value = 0,001	p-value =0,001	p-value= 0,004
	Longitudinal x transversal	NS	NS	NS
	Patches	p-value = 0,001	NS	NS

Table 4

(a)	Banks		Channel	
	Reference	Contaminated	Reference	Contaminated
Richness	20 ± 8	10 ± 2	16 ± 6	10 ± 6
Abundance	746 ± 578	619 ± 604	4347 ± 4665	595 ± 733
EPT %	25 ± 24	5 ± 6	5 ± 8	12 ± 19
Diptera %	27 ± 18	22 ± 12	61 ± 26	52 ± 34
Mollusc %	3 ± 4	0.59 ± 0.84	1 ± 2	0.48 ± 0.78
Gammarus %	20 ± 21	17 ± 18	6 ± 8	6 ± 12
Functional diversity	0.72 ± 0.16	0.56 ± 0.29	0.56 ± 0.27	0.51 ± 0.28
Taxonomic diversity	2.57 ± 0.73	1.83 ± 0.96	1.83 ± 1	1.71 ± 1
Equitability	0.42 ± 0.12	0.30 ± 0.16	0.30 ± 0.17	0.28 ± 0.18

(b)	Erosion		Sedimentation	
	Reference	Contaminated	Reference	Contaminated
Richness	19 ± 6	15 ± 4	15 ± 4	7 ± 2
Abundance	1553 ± 3461	220 ± 81	3965 ± 3873	812 ± 733
Functional diversity	0.71 ± 0.26	0.81 ± 0.03	0.57 ± 0.06	0.33 ± 0.2
Faunistic diversity	2.61 ± 1	2.89 ± 0.28	1.70 ± 0.33	1 ± 0.65

Table 5

Variables	**Interaction**	**Status factor**	**Habitat factor**
Abundance	$p = 0.44$	$p = 0.46$	$p = 0.03$
Richness	$p = 0.57$	**$p = 0.01$**	**$p < 0.001$**
Taxonomic Diversity	$p = 0.17$	$p = 0.17$	$p < 0.001$
Functional Diversity	$p = 0.06$	$p = 0.19$	$p < 0.001$