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Céline Becouze-Lareure, Gislain Lipeme Kouyi, Carolina Gonzalez-Merchan, Christine Bazin, Christel Sebastian, et al.. Spatial and temporal dynamics of sediment ecotoxicity in urban stormwater retention basins: Methodological approach and application to a pilot site close to Lyon in France. *Journal of Environmental Science and Health, Part A*, 2018, 53 (13), pp.1123-1130. 10.1080/10934529.2018.1529894 . hal-02056170

HAL Id: hal-02056170

<https://univ-lyon1.hal.science/hal-02056170v1>

Submitted on 27 Feb 2024

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Spatial and temporal dynamics of sediment ecotoxicity in urban stormwater retention basins: Methodological approach and application to a pilot site close to Lyon in France

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To characterize the spatio-temporal variation of sediment ecotoxicity in a retention/detention basin, a monitoring program using the *Heterocypris incongruens* bioassay was carried out for 72 months (5 years) on a field basin close to Lyon in France. Results showed that the variation of ecotoxicity is relatively small from one location of the basin to another, apart from sediment sam-pling collected in an open-air chamber located in basin supposed to collect gross pollutants and hydrocarbons. Regarding the temporal variation of ecotoxicity, the bioassays also showed a slight variation between 6 and 72 months. On the contrary, they highlighted the high ecotoxicity of the “fresh” sediments collected during rain events using sediment traps. Additional investigations are needed to understand the period of inflexion of ecotoxicity, occurring between 24 h and 6 months. These results can be used by practitioners of urban facilities and networks to improve maintenance strategies of retention/detention basins.

Introduction

Stormwater retention/detention basins and the ecotoxicity of their sediments

Stormwater retention/detention basins are now often incorporated in urban stormwater management systems. They fulfill two main roles: (i) to reduce flood risks and (ii) mitigate the pollution of aquatic environments through the settling of pollutants (metallic compounds, hydrocarbons, etc.) bound to suspended solids.^[1,2] Settling processes lead to the accumulation of contaminated sediments at the bottom of these basins^[3–6] that then have to be managed. However, there is a lack of data in the scientific literature on the characterization and the long-term evolution of the sediments ecotoxicity. Their characterization generally involves global parameters (humidity, content in volatile matters, content in nitrous compounds, etc.) and the presence of several families of chemical substances such as heavy metals and hydrocarbons.^[7–9] The in-depth ecotoxicological characterization of sediments is necessary to optimize their management and define the appropriate elimination or recovery procedure after cleaning. Indeed, the chemical characterization enables to identify several chemical components involved in the toxicity of sediments,^[10–13] but it is not enough as it does not integrate the detailed chemical interactions (“cocktail” effect^[14,15]) of the pollutants present in the sediment samplings. All interactions between pollutants (synergetic and/or antagonistic effects) can

considerably modify the ecotoxicity of the global matrix. Thus, the solution for obtaining this global assessment is to carry out bioassays (or ecotoxicity tests) on the targeted matrix or ecosystems.^[16,17] Consequently, a battery of adapted bioassays was prepared for studying sediments sampled from this type of basin.^[18] This battery was formulated on the basis of results from initial works performed on urban sediments,^[19–21] showing the need to work with organisms adapted to this type of material and highly sensitive to pollution, given the moderate ecotoxicity of urban sediments in comparison to matrices often studied by ecotoxicologists (wastes, polluted industrial soils, etc.).^[22–24]

Objectives of the project

The objective of this article is to characterize the spatial-temporal evolution of the ecotoxicity of sediments in a stormwater retention/detention basin by means of *Heterocypris incongruens* bioassay. This article aims to provide information on the ecotoxicity of sediments collected at specific locations and times in a basin and allows identifying appropriate recommendations for the maintenance of such systems.

Materials and methods

Presentation of the field retention/detention basin

The field retention/detention basin is located at Chassieu (a city close to Lyon in France). It drains stormwater from an

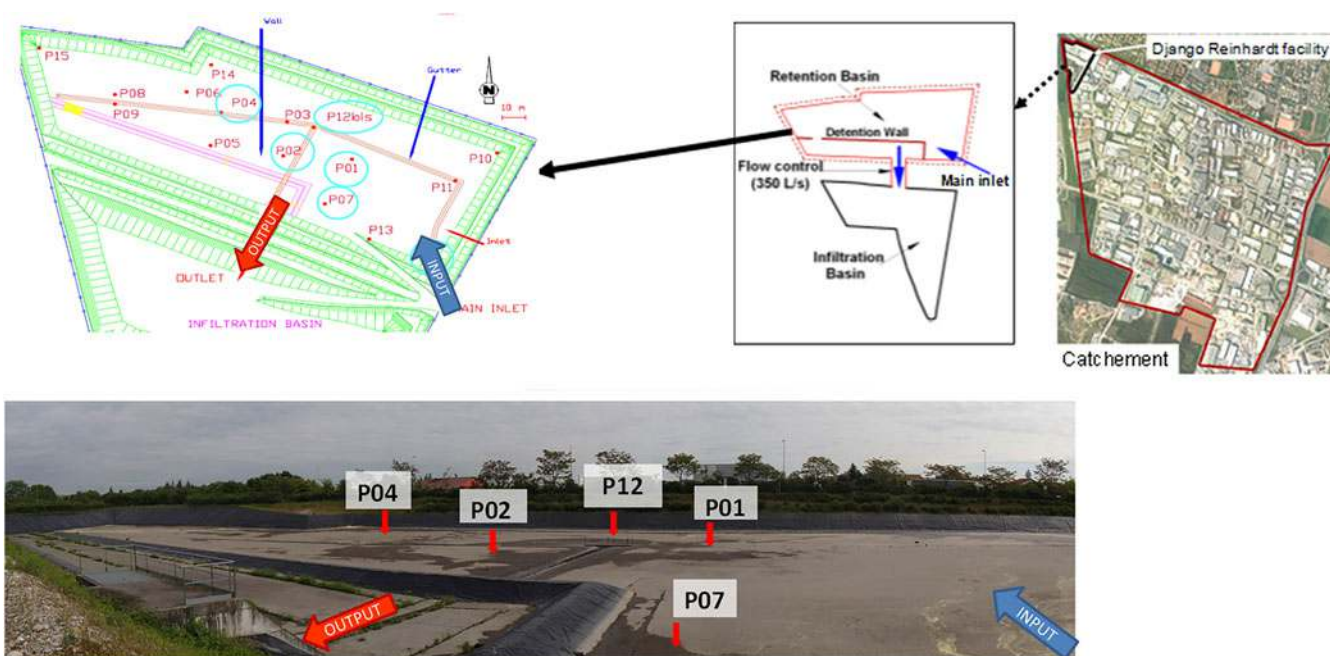


Figure 1. Selected location to collect sediment samples.

industrial catchment area covering 185 ha, with an average slope of 0.4% and an impervious coefficient of about 75%. The catchment is drained by a separated stormwater network supplying a system composed of the retention/detention basin linked to an infiltration basin. The article only addresses the characterization of the sediments in the first compartment (the retention/detention basin) supposed to trap polluted particles by settling and prevent the infiltration part from clogging. The volume of the basin is 32,000 m³ with a bottom area of approximately 1 ha. The basin was cleaned in 2006, then in March 2013. Five sampling points were selected based on the spatial distribution and amount of sediments.^[9,25] Figure 1 shows their location.

To have enough sediments for sampling and analysis, as well as to account for potential seasonal effect, four successive sampling campaigns were performed. The first was performed before the basin cleaning (sediment age: 72 months), the others were performed 6 months, 15 months and 37 months after the cleaning.

Among these points, P12 is a particular sampling site. In this point, there is a small open-air chamber supposed to trap gross pollutants and hydrocarbons. The sediments from this point were taken at the bottom of the chamber.

Sampling of sediments accumulated in the basin

The quartering method was used to sub-sample the sediments^[26] and guaranty the representativeness of the samples collected (Fig. 2). Finally, the sediments collected (≈ 1 kg) were packed and placed in different containers for chemical and ecotoxicological analyses.

Sampling of fresh sediments (sediment trap)

The fresh sediments settled during a storm event were collected using sediment traps placed at the bottom of the

basin. Each trap was composed of three plastic tanks equipped with a “bee nest” structure to reduce the resuspension of particles trapped (Fig. 3). The traps were fixed at the bottom of the basin with iron bars to prevent them from moving and floating during storm events.

Transport and conservation of samples

After field sampling, the samples were transported rapidly to the laboratory and then kept in a cold chamber at 4 °C before sub-sampling and/or chemical analyses. Due to the time required to perform the bioassays, the samples were frozen.

Physical and chemical analyses

The physical and chemical analyses (standards and protocols) performed on the sediments are presented in Table 1. The aim of the global parameters is to facilitate interpreting the results. The heavy metals were monitored as their presence was almost systematic in this type of sediments^[8–10] and known to be toxic for most of them.

The bioassay selected: the ostracod test

Among the bioassays on the sediments selected and tested during previous studies,^[18,21,27] the ostracod (*H. incongruens*) sub-chronic test was chosen for this study due to its higher sensitivity, the possibility of working directly on the solid matrix and its greater ecological representativeness in comparison to other bioassays initially proposed for liquid phase samples, such as the commercial test kit Microtox®-Solid Phase test^[28] with *Vibrio fischeri* (provider’s protocol for sample preparation and ISO 11348-3 standard) or *Daphnia magna*^[21] (NF EN ISO 6341 standard). This

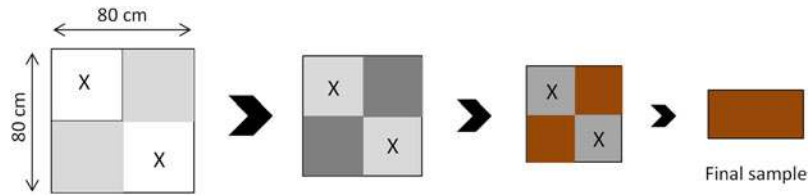


Figure 2. Quartering method.



Figure 3. Photo of sediment traps.

ostracod test was performed in conformity with the instructions of standard ISO 14371,^[29] using the percentage of mortality of organisms after 6-days exposure to the sediment samples. The possibility of measuring the growth inhibition of the organisms was not explored here, due to the possible interference of organism growth stimulation through the contribution of nutritive substances and/or hormesis (stimulation of organisms via weak doses of toxic compounds), as it had already been observed during previous studies.^[18]

Results

Physical and chemical analyses

The results of the physical and chemical analyses are presented in Tables 2 and 3.

Accumulated dry sediments are fine with median diameter around 50 μm , except for those collected from locations P01 ($d_{50} = 193 \mu\text{m}$) and P12 ($d_{50} = 172 \mu\text{m}$). P01 and P12 are close to the inlet point of the basin. That may explain these highest values of median diameter of accumulated sediments at these locations. Indeed, Jacopin et al.^[30] demonstrated the same trend (i.e., relationship between the distance from the inlet of a retention/detention basin and the grain size of settled sediments); the finest particles being found in the furthest part from the inlet. P12 is also a chamber dug in the bottom of the basin and plays the role of a gross sediment trap.

Apart from P01 and P12, for both accumulated and fresh trapped sediments during a storm event, the spatial distribution of median grain size seems similar from one point to another and approximately in the same range at 6 months

Table 1. Standard and protocols related to physical and chemical analyses.

Analysis	Method	Standard
Particle size	Laser Particle Sizer Technique (Malvern Mastersizer 2000 granulometer) with ultrasound at 100% for 5 min	NF ISO 13320-1 (2009)
Volatile organic materials	Loss by combustion 550 °C	NF EN 12879 (2000)
Metals	ICP-AES	NF EN ISO 11885 (2009)
C_{total}	Combustion at 1300 °C	NF ISO 10694 (1995)
N_{total}	Titrimetric method after distillation	NF U 42-151 (1984)
P_{total}		NF EN ISO 11885 (2009)

compared to 15 months (d_{50} between 40 and 92 μm). At 72 months, the grain size was finer whatever the point compared to those obtained at 6 and 15 months. This result is in accordance with previous results indicating an accumulation of fine particles coming from storm events.^[9,30]

Nutrient and organic contents are slightly higher in fresh trapped sediments. Total phosphorus, total nitrogen and total organic carbon contents are similar from one location to another.

Heavy metal contents are also slightly higher in trapped sediments. These contents are similar from one location to another, with a low spatial variation coefficient of 5%. Regarding accumulated sediment, the sediments in P02 and P04 were a little more polluted at 6 months than at 15 months for nearly all the heavy metals.

Both trapped and accumulated sediments showed high concentrations in heavy metals. Most of them presented concentrations over the target values of Dutch standards.^[31] Cu and Zn even showed values higher than the intervention thresholds.

Spatial evolution of ecotoxicity

Figure 4 corresponds to the representation of ecotoxicity (in this case ostracod mortality) as a function of the sediment sampling point for each sampling campaign (6 months, 15 months, 37 months and 72 months). Results show that the ecotoxicity level is almost similar for all locations, except for P12 and in a lesser extent for P07 (particularly after 6 months of accumulation). Indeed, P12 location corresponds to the sediment chamber located in the basin. This chamber may be considered as an inner reactor with high humidity of sediment, significant PAH concentration and leading to microorganism activities.^[32] This chemical and microbiological dynamics could explain the high level of ecotoxicity at this location P12.

Table 2. Results of physical and nutrients analyses of sediments.

	Granulometry d50 (pm)									Organic Volatile Matter (%)									N _{tot} (%)			C _{tot} (%)			P _{tot} (mg/kg DM)		
	6 months			15 months			72 months			6 months			15 months			72 months			6 months			15 months			72 months		
	6 months	15 months	72 months	6 months	15 months	72 months	6 months	15 months	72 months	6 months	15 months	72 months	6 months	15 months	72 months	6 months	15 months	72 months	6 months	15 months	72 months	6 months	15 months	72 months			
P01	Accumulated sediments	193.6	141.1	37.1	5.9	22.8	21.2	0.1	0.3	0.4	0.4	5.7	9.2	10.3	55.3	142.0	1219										
	Fresh sediments	108.3	68.0	nm	25.8	27.5	nm	0.9	0.8	nm	18.8	16.9	18.8	1429	1540	nm											
P02	Accumulated sediments	67.9	89.3	50.4	21.3	18.7	17.7	0.4	0.5	0.4	13.1	12.6	10.0	1368	1460	1278											
	Fresh sediments	92.1	56.8	nm	27.9	28.7	nm	0.7	0.7	nm	22.6	16.4	nm	1445	1580	nm											
P04	Accumulated sediments	45.2	60.8	33.9	22.5	20.8	25.5	0.6	0.6	0.7	15.3	14.0	10.8	1234	1330	1345											
	Fresh sediments	82.3	62.7	nm	26.3	27.4	nm	0.7	0.8	nm	18.1	15.2	nm	1327	1640	nm											
P07	Accumulated sediments	48.2	71.3	33.9	17.1	21.1	25.6	0.3	0.6	0.5	12.2	12.6	10.0	923	1370	1223											
	Fresh sediments	82.9	38.5	nm	25.9	26.3	nm	0.7	0.7	nm	19.5	14.8	nm	1344	1400	nm											
P12	Accumulated sediments	172.3	534.6	61.6	19.0	3.1	17.9	0.6	<0.1	1.7	11.6	2.8	9.6	1096	531	1432											
	Fresh sediments	83.9	88.2	nm	26.2	27.6	nm	0.8	0.6	nm	22.8	16.7	nm	1245	1470.0	nm											

Nm: not measured.

Table 3. Heavy metal contents (mg/kg DM) in the collected sediments.

	Cd			Cr			Cu			Ni			Pb			Zn			
	6 months			15 months			72 months			6 months			15 months			72 months			
	6 months	15 months	72 months	6 months	15 months	72 months	6 months	15 months	72 months	6 months	15 months	72 months	6 months	15 months	72 months	6 months	15 months	72 months	
P01	Accumulated sediments	0.7	1.7	4.1	70	58.2	156	138	267	271	42.0	30.6	92	67	127	135	610	1790	1558
	Fresh sediments	1.8	1.7	nm	151	57.8	nm	319	256	nm	88.0	28.5	nm	131	116	nm	1898	1850	nm
P02	Accumulated sediments	1.7	1.6	3.1	129	63.9	158	285	250	280	75.0	32.0	97	141	129	127	1673	1790	1534
	Fresh sediments	1.9	1.8	nm	142	59.4	nm	336	250	nm	90.0	29.0	nm	149	119	nm	2037	1760	nm
P04	Accumulated sediments	1.7	1.6	5.6	113	53.3	137	275	230	308	72.0	26.1	81	138	112	201	1503	1750	1663
	Fresh sediments	2.2	1.8	nm	128	58.4	nm	303	249	nm	76.0	28.9	nm	138	117	nm	1916	1700	nm
P07	Accumulated sediments	1.5	1.5	6.6	122	53.7	130	222	218	279	67.0	26.4	82	131	118	231	1358	1610	1508
	Fresh sediments	1.8	1.7	nm	133	57.7	nm	322	244	nm	77.0	26.3	nm	144	112	nm	2130	1640	nm
P12	Accumulated sediments	1.1	0.6	1.7	111	18.3	113	229	99	213	68.0	11.0	60	115	22	123	1380	423	1590
	Fresh sediments	1.9	1.7	nm	127.0	54.0	nm	360	262	nm	78.0	28.3	nm	130	107	nm	1739.0	1600	nm

Nm: not measured.

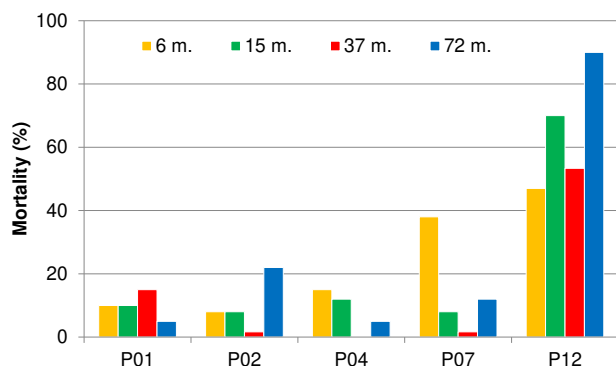


Figure 4. Spatial evolution of ecotoxicity of accumulated sediments.

Temporal evolution of ecotoxicity

Evolution of sediment ecotoxicity between 6 and 72 months

Figure 5 shows the ostracod mortality as a function of the period of sediment sampling for each sampling point (P01, P02, P04, P07 and P12). This figure shows that the variation of ecotoxicity with time (in the period from 6 to 72 months) is not significant for each location.

Comparison between fresh and accumulated sediment ecotoxicity

Figure 6 shows the ostracod mortality as a function of the level of sediment maturation: fresh sediments sampled during rainfall events using sediment traps versus old sediments accumulated for 6, 15 and 37 months in the basin. This figure shows a strong difference between fresh trapped and old dry accumulated sediment ecotoxicity levels.

Discussion

Overall level of ecotoxicity

Based on the same bioassay, the ecotoxicity of the sediments sampled in the retention/detention basin is in the range of values observed in other sediments taken from various urban environments such as reservoirs and small urban streams under various stormwater discharges conditions.^[33–36] Despite a high level of pollution in heavy metals, the ecotoxicity, except for point P12 is rather low (mortality <30%).

Spatial variation of sediment ecotoxicity

The variation in pollutant concentration and in the resulting ecotoxicity of the sediments between the different sampling locations, potentially depends on the basin configuration and especially on its hydrodynamic behavior.^[25,37,38] Our initial assumption was the link between different levels of ecotoxicity and the grain size of the particles (Table 2). The finer particles being generally more polluted,^[39–42] we expected a higher ecotoxicity in the locations where fine particles predominated. We also knew from previous study that the most ecotoxic part in stormwater was the particulate and not the dissolved phase.^[43] Except for P12 and to

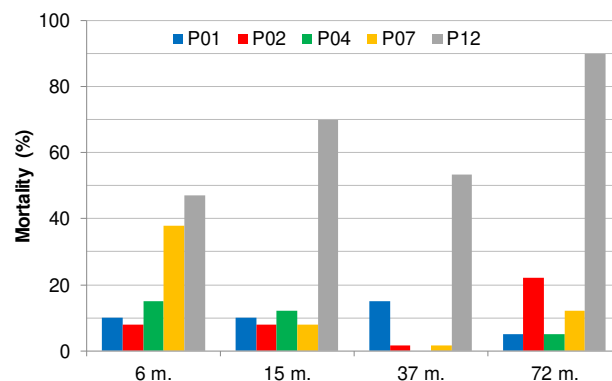


Figure 5. Evolution of ecotoxicity in sediments accumulated between 6 and 72 months.

lesser extent P01 which were particular points, the grain size and the physico-chemical characteristics were rather homogeneous in space and the variation of ecotoxicity relatively low from one location to another. With the same level of metallic contamination, the ecotoxicity of the sediments in P12 was much higher than in the other points.

The article shows a relative spatial stability of sediment ecotoxicity in stormwater retention/detention basins that has never been described before in the scientific literature.

Temporal variation of sediment ecotoxicity

Variation between fresh and accumulated sediments over time

A significant difference of sediment ecotoxicity between the period of trapping sediments during rainfall events (fresh sediments) and after several months of the accumulation of dry sediments was highlighted. The results obtained with the same bioassay as Angerville et al.^[21] on fresh sediments from two other sites and prepared by the filtration of stormwater from combined sewer systems, showed that fresh particles were highly ecotoxic. Angerville et al.^[21] outcomes support the results obtained from the fresh sediments in this study. This phenomenon of sediment “detoxification” with time could be due to the volatilization of specific volatile compounds (ammoniac, chlorinated solvents, BTX and other volatile organic compounds (VOCs)), and/or to the biodegradation/photodegradation of ecotoxic organic compounds (e.g., biodegradation of PAH by certain microorganisms^[32]). At the same time, the physico-chemical analyses presented in Table 2 show a higher organic matter content for the fresh sediments in comparison to the matured ones. This phenomenon of “detoxification” could also be due to a change in the physico-chemical conditions in the sediments, susceptible to lead to a modification of the solubility and availability of certain pollutants. These different phenomena have already been observed in various works focusing on the materials akin to urban sediments, such as the sediments of contaminated rivers^[44–46] or sludge from wastewater treatment plants.^[47] In addition, pollutants monitored in this study (selected heavy metals and nutrients) may not explain all dynamic of the ecotoxicity. Biochemical interactions and transformations (e.g., due the significant

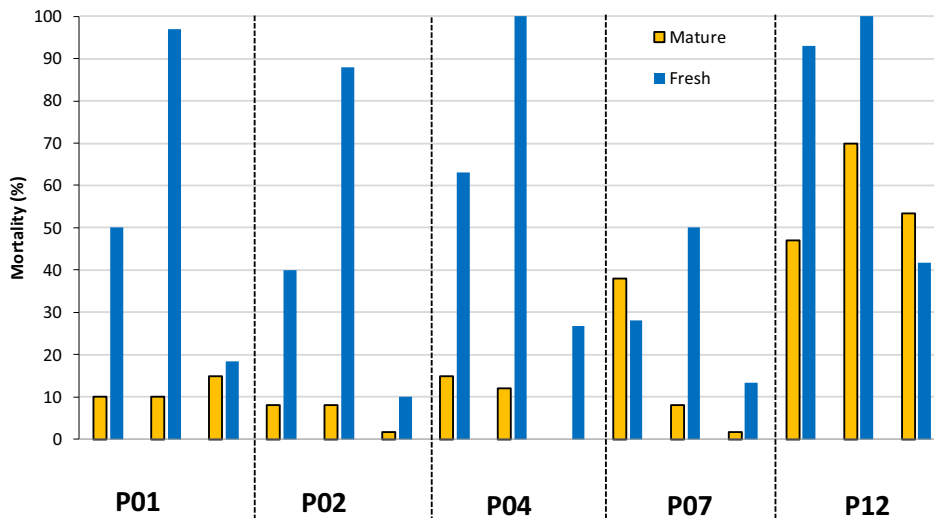


Figure 6. Ecotoxicity of accumulated and fresh sediments.

concentrations of PAH and bacteria counts – see Marti et al.^[32]) could explain the decrease of ecotoxicity with aging.

Variation of ecotoxicity between 6 and 72 months

The variation of sediment ecotoxicity between 6 and 72 months is low and shows that most of the phenomena mentioned above may occur before 6 months.

Recommendations for sediment management

The two main recommendations for managing sediments that can be made following these research findings are the following:

1. An ecotoxicity test, like the ostracod test, could be performed on the sediments accumulated in different zones of the basin to determine the most appropriate sediment management strategy to be applied. In current areas, a mix of sediments sampled all over the basin could be taken for the test. If specific devices are present in the basin like the one in P12, sediments from these area should also be tested separately. In our case, the sediments of point P12 cannot probably be recovered and must be removed and treated (e.g., in incineration plant or deliver to a dedicated dump). The less ecotoxic sediments can be used as resource recovery.
2. The sediments should be left in the retention basin for weeks or several months to decrease its ecotoxicity level by aging and then may be discharged to a dedicated resource recovery plant. Additional investigations are needed to strengthen the ostracod bioassay by testing correlation with relevant chemical contaminants for example.

Conclusion

Investigations carried out led to better understand the spatial-temporal variation of sediments ecotoxicity in a

retention/detention basin. Derived results demonstrated that the ostracod (*H. incongruens*) ecotoxicology test performed to carry out this characterization is robust and appropriate and could be useful for sediment management of such basins.

Sediments trapped at P12 (inner sedimentation device) have the highest level of ecotoxicity and should be avoided. Anyway, the size of such device is too small to be efficient in pollutant trapping and resuspension is generally observed. Results also showed that fresh sediments are more ecotoxic than aging sediments left in the bottom of the basin. All these new insights will be useful for managers to optimize sediment management procedures and maintenance strategies for these basins.

To consolidate and validate the approach developed, it is now necessary to perform the same work on other stormwater retention/detention basins, by selecting a large diversity of such structures. Furthermore, the approach developed can be improved in several ways. In particular, the ostracod bioassay could be completed with other bioassays performed on organisms belonging to other trophic levels. However, the selection of the organism involved in bioassays must be done carefully. An additional challenge is related to the determination of the minimum period needed to guarantee sediment detoxification, probably between 24 h and 6 months.

Funding

This study was funded by the ANR (French National Research Agency) (project “CABRES”, reference: ANR-2011-CESA-012). The authors thank the Field Observatory for Urban Water Management (OTHU – www.othu.org/ – FED 4161), the Greater Lyon, the Rhône-Mediterranean Water Agency and the Auvergne Rhône-Alpes Region for their scientific and financial supports.

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