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Detention of urban runoff in a park - Effects on organic micropollutants

Effets d'un jardin public inondable sur la contamination en micropolluants organiques des eaux pluviales urbaines

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ABSTRACT

Over the last decades classic stormwater drainage by pipes has been completed or replaced by systems that manage stormwater at upstream scale. These sustainable urban drainage systems (SUDS) are usually designed for hydraulic purposes and they may have an incidence on the contaminant loads conveyed by storm waters. But few studies are available for assessing these effects. In this paper, we will consider a park used as a runoff detention basin for buildings (roof and garden) and an impervious play garden, in a periurban area near Paris. Stormwater contamination was compared both in entries (atmospheric fallout and building runoff) and at the outlet. Emitted mass decreased during water detention for polycyclic aromatic hydrocarbons (PAHs: 37 %), polychlorobiphenyles (PCBs: 74 %) and nonylphenols (NPs: 82 %). Involved mechanisms are supposed to be particles settling and adsorption of dissolved substances. A different behaviour has emerged for PAHs : they are less retained during detention than water volume. A possible explanation could be that fine particles contaminated by PAHs were released by the garden. Contents in soils and plants of the garden showed no apparent degradation of the garden quality due to runoff detention.

KEY WORDS

Detention, priority substances, stormwater, SUDS.

RÉSUMÉ

La gestion des eaux pluviales par des techniques alternatives qui stockent l'eau à une échelle amont est de plus en plus utilisée pour relayer les réseaux d'assainissement surchargés. Ces techniques peuvent influencer la qualité des rejets mais peu d'études ont quantifié cet effet. Ce travail de recherche porte sur le stockage des eaux de ruissellement de plusieurs parcelles bâties et d'une aire de jeu imperméabilisée dans un jardin public inondable, en zone périurbaine près de Paris. L'étude de la contamination des eaux en entrée (retombées atmosphériques et ruissellement du bâti) et en sortie, a prouvé une diminution de l'émission des masses d'hydrocarbures aromatiques polycycliques (HAP : 37 %), de polychlorobiphényles (PCB : 74 %) et de nonylphénols (NP : 82 %). Les mécanismes impliqués semblent être la décantation des particules et l'adsorption des fractions dissoutes. Un phénomène supplémentaire est apparu pour les HAP dont la masse diminue moins que le volume d'eau. Une explication possible serait l'émission par le jardin de fines particules contaminées en HAP. L'étude des teneurs dans le sol et les plantes du jardin n'a pas montré de dégradation apparente de la qualité du jardin suite au stockage.

MOTS CLÉS

Eaux pluviales, gestion amont, stockage, substances prioritaires, techniques alternatives.

1 INTRODUCTION

Stormwater management is an important issue for sustainable development in urban areas both in order to protect people against flooding and because runoff is one of the most important sources of water quality degradation in surface waters (Burton and Pitt, 2002; Brombach et al., 2005). Over the last decade, classic stormwater drainage by pipes has been completed or replaced by systems that manage stormwater at upstream scale. The aim of these sustainable urban drainage systems (SUDS) is to get closer to the natural water cycle by improving retention of rainfalls, slowing down water discharge and increasing infiltration into sub-soil. SUDS are usually designed for hydraulic purposes and intended to the management of heavy rain events. As they slow down runoff flows, raise retention times and increase infiltration volumes, they may also have an incidence on the contaminant loads conveyed by storm waters (Jefferies et al., 2003). However, this effect is not yet clearly quantified (Daywater, 2003; Jefferies et al., 2003).

In order to achieve the objective of “good ecological status” of the aquatic environment by 2015, as required by the Water Framework Directive (2000/60/CE), it seems necessary to quantify fluxes of pollutants in stormwater and assess ability of drainage systems to improve water quality.

In this paper, we will consider a park used as a runoff detention basin in a periurban area near Paris. The objectives of the study are to evaluate the effect of this SUDS firstly on the runoff contaminant load from the considered catchment, secondly on the contamination level of soils and plants in the park. An analysis of the processes that may occur inside the storage system will also be attempted. Studied micropollutants are polycyclic aromatic compounds (PAHs), nonylphenols (NPs) and polychlorobiphenyls (PCBs). They are all toxic for aquatic environment, persistent and hydrophobic. PAHs are products of organic matter combustion. NPs are metabolites of nonylphenols ethoxylates, which are widely used as surfactants in domestic, industrial and agricultural products. PCBs are synthetic products prohibited for production since 1987 but always present in environment. PAHs and NPs are priority substances from the Water Framework Directive.

2 MATERIAL AND METHODS

2.1 Site characterization

The catchment area (Figure 1) consists in 4 building lots (8291 m², 32 % roofing surface, 6 % other impervious surface, 62 % above slab gardens with underlying drainage system) surrounding a public park (7637 m²). Stormwater collected by the private drainage systems of the building lots is directed into this park, where it is temporarily stored in two interconnected grassed retention basins. These basins also collect stormwaters from the impervious paths of the park and from an impervious playground (3658 m²). The flow at the outlet of the park is limited to 23 l/s by a flow regulator and is rejected into the municipal stormwater sewerage system after pretreatment in a hydrocarbon separator.

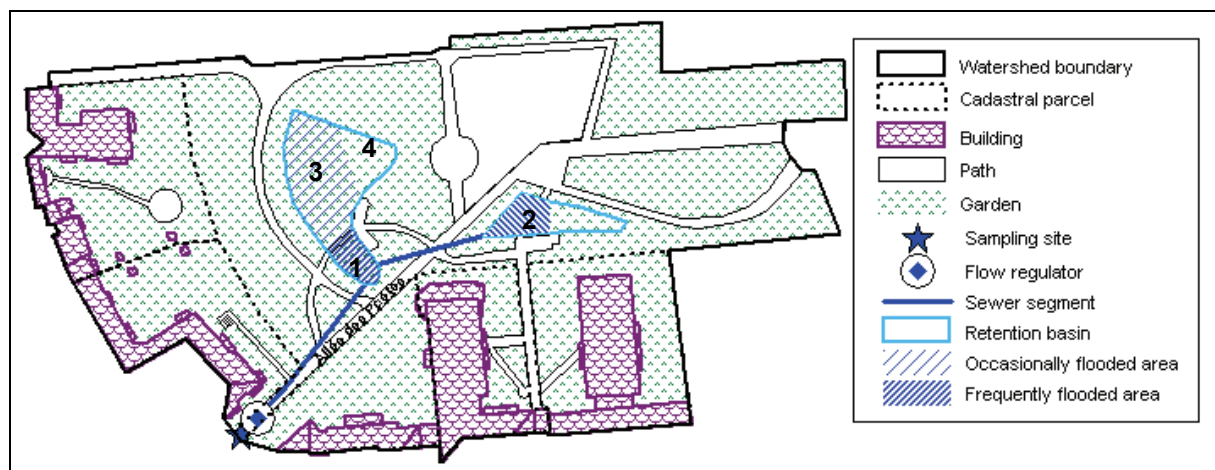


Figure 1: Map of studied catchment

2.2 Sampling strategy

This study attempts to:

- establish an entry-exit mass balance of organic contaminants at the scale of the considered watershed
- analyse the fate of these micropollutants inside the stormwater management system, and especially their potential to contaminate soils and plants inside the park.

Thus samples representative of the contaminant load entering the park (bulk atmospheric deposition and runoff from a building lot) and leaving the park (stormwater at the outlet of the park, after the hydrocarbon separator) have been collected, as well as samples representative of the soils and the plants of the park and sediments from the hydrocarbon separator.

2.2.1 Total atmospheric deposition and stormwater

Bulk atmospheric deposition (dry and wet) was sampled in a glass amber bottle connected to a 1 m² stainless steel collector located on the highest roof about 400 m from the site. The sampling period included the studied rain event and the preceding dry weather period. Runoff from a nearby building lot (including zinc roof, flat roof and above slab garden) and from the catchment outlet was sampled with automatic samplers controlled by flow-meter to obtain the averaged concentrations over the rain event. Sampling was done in glass.

Six events were sampled between October 2008 and April 2009. Event characteristics are given in Table 1. Rainfall depth and rainfall intensities are relatively low and typical of frequent events.

Date	Raindepth (mm)	Max. 6-min rainfall intensity (mm/h)	Return period (month)
10/21/08	8	6.1	0.2
10/26/08	21.2	13.5	0.5 - 6 ¹
11/11/08	10.8	24.7	1 - 2 ¹
11/23/08	7.6	7.2	0.2 - 0.5 ¹
03/04/09	10.6	3.1	0.2 - 1 ¹
04/07/09	12.6	9.9	0.5 - 3 ¹

Table 1: Characteristics of sampled events

(¹ return period was calculated both from rain depth and max 6-min rainfall intensity)

2.2.2 Soils samples

The surface of the retention basins has been divided into four areas according to their flooding frequency: area 1 and 2 are flooded at each rain, area 3 is occasionally flooded, and area 4 is very seldom flooded. An average soil sample has been collected from each of these 4 areas for the upper 5 cm of soil layer, and for the 5-15 cm depth soil layer. In order to constitute these average soil samples, 4 to 6 samples have been collected with a drill (20 cm long), in each area, following a grid with a mesh of 7 m², and mixed together. One sample has been analysed in triplicate for variability assessment: signal deviation was lower than 20 %.

The wetland plants (iris, cattail and rush) that are growing in area 1, along the main flow path, have also been collected (roots, stems and leaves) and analysed.

Deposits have been observed in HC separator: around 5 cm of sludge composed by fine and clear particles. Averaged samples have been collected in by pumping.

2.3 Analytical procedure

Analytical procedure is based on separation between dissolved and particulate fractions both in order to prevent an underestimation of the contamination loads (Zgheib et al., 2009) and to give interesting information about contaminant speciation. All the procedure is performed in glassware cleaned with detergent, then MilliQ water, and calcined at 500 °C for 8 h. Solvents are chromatography grade.

2.3.1 Dissolved and particulate organic carbon

Dissolved organic carbon (DOC) and particulate organic carbon (POC) concentrations were measured

after filtration on precombusted GF/F filters and acidification, using a carbon analyser (O.I. Analytical College Station, TX, USA).

2.3.2 Organic micropollutants

The analytic method was already described by Bressy et al. (2009). Runoff and atmospheric deposition samples were filtered through 0.7 µm glass fibre filter (GFF Whatman), immediately after the sampling and a maximum of one day after the rain event to preserve speciation.

Dissolved fractions were extracted on 2g C18 cartridge (Macherey-Nagel). Particulate fractions, plants, deposits and soil samples were freeze dried then extracted by microwave-assisted extraction (Soxwave 3, Prolabo). The three pollutant families were separated during a purification step on silica columns.

Contaminants were quantified by internal calibration with a GC/MS (Focus DSQ, Thermo Fisher Scientific). Internal standards (IS) had been spiked prior to extraction (IS are deuterated molecules: 4-n-octylphenol-D11, 4-n-nonylphenol-D4 (CDN Isotopes); naphthalene D8, acenaphthene D10, phenanthrene D10, chrysene D12, perylene D12 (Mix 13, Dr. Ehrenstorfer); and PCB 36, PCB 112, PCB 209 (Ultra Scientific-RPC-060S, LGC Promochem)).

Results are displayed in sum of 16 PAHs of the list of priority substances for the US Environmental Protection Agency and sum of the 15 PCBs from the commercial solution PCBmix NE-USL¹ (LGC Promochem), not counting naphthalene, acenaphthene, acenaphthylene and PCB18 which are too volatile to be correctly quantified.

3 RESULTS

3.1 Hydrological behaviour

The effect of on site-storage on contaminant loads will be largely dependent on the hydrological behaviour of the system. The hydrological performance has been evaluated via:

- comparison between the flow dynamic measured at the outlet of the park to the rain dynamic;
- comparison between runoff volumes measured at the park outlet to runoff volume that would have been generated with a conventional storm sewerage system.

3.1.1 Qualitative observations

The main effect of detention garden is levelling of the rain variations, with significant flow-rate peak attenuation. Indeed the maximum measured flow-rate is 2.9 l/s, it corresponds to 1.5 l/s/ha. This value is much lower than 10 l/s/ha which is imposed by the local government. So the water flow is strongly slowed, which promotes settling. Moreover the discharge is spread over the time: water flow appeared between 1.5 and 4 hours after the beginning of the rain event and stopped between 5 - 24 hours after the end of the event.

3.1.2 Quantitative effects

It was considered that in a conventional system, runoff from the building lots, from the play-garden and from the impervious paths of the park would flow into a storm sewer, whereas the pervious surface of the public garden would not have been connected to the sewerage system.

The runoff volume that would have been produced with conventional drainage systems was calculated as following:

$$V_{\text{simul}} = H \cdot (RC_p \cdot S_p + RC_b \cdot S_b + RC_g \cdot S_g) \quad \text{Equation 1}$$

Where H is the rain depth; S_p , S_b and S_g the areas of paths, constructions and private garden surfaces; and RC_p , RC_b and RC_g the runoff coefficients of paths, constructions and private gardens.

The theoretical runoff coefficients have been estimated according to the literature values and adjusted for each rain event based on flow measurements performed on a classic separate sewer watershed in the same town district. Therefore they vary according to the rainfall intensity and to the initial wetness of the catchment: $RC_b = 0.8$ to 1, $RC_p = 0.6$ to 0.9, $RC_g = 0$ (for 2 rain events) to 0.7.

Table 2 allows the comparison between the impervious coefficient (C_{imper} calculated from the land use

¹ PCB : 18, 31, 28, 20, 52, 44, 101, 149, 118, 153, 105, 138, 180, 170, 194

pattern), the simulated runoff coefficient ($C_{\text{runoff_sim}}$: ratio between the simulated volume and the volume calculated from the rain depth) and the runoff coefficient (C_{runoff} : ratio between the volume measured by the flow meter and the volume calculated from the rain depth). C_{imper} and $C_{\text{runoff_sim}}$ are very close which is not surprising. Indeed the simulation took into account the fact that private gardens are above slab with underlying drainage system. This kind of gardens rejects more stormwater than classic gardens because there is no infiltration into sub-soils. Difference between measured and simulated runoff coefficients is really important and proves stormwater volume reduction (68 %) during detention. Water losses are due to higher initial losses in the soil of the park, improvement of infiltration, and the storage of a residual volume in the park after the event that would be evaporated or evapotranspired.

C_{imper}	$C_{\text{runoff_sim}}$	C_{runoff}
0.57	0.62	0.2

Table 2: Impervious and runoff coefficients, and comparison between simulated and measured volumes

3.1.3 Conclusion on hydrological behaviour

These observations show important runoff volume and peak flow reductions. Moreover the design of the retention garden allows a slowdown of the passage of water. It could improve settling of particles or exchanges of contaminants between phases compared to classic separate sewer and so have an effect on discharged pollutant loads.

3.2 Effects on emitted organic micropollutants

In this section, the aim was to analyse if stormwater storing in the garden has an effect on rejected micropollutants. Firstly concentrations at the outlet of the retention basin were compared with concentrations of runoff entries, both in total and dissolved fractions. Then mass balances at the scale of the event have allowed this effect to be quantified.

3.2.1 Effects on concentrations

The watershed is only supplied by the atmosphere and the buildings. Concentrations measured in these two sources and at the outlet are displayed in Figure 2 with scattergrams (measured values and median) in both total and dissolved fraction.

Concentrations observed in building runoff were significantly higher than in atmospheric fallout for SS ($\times 12$), TOC ($\times 8$), PAHs ($\times 5$), NPs ($\times 4$) and PCBs ($\times 2$). These important levels of SS and TOC in the building runoff should probably be attributed to the erosion of soils from the gardens during heavy rainfalls, or to the erosion of deposits build up inside the drainage system of the building lot for the other rain events. HAP and PCB releases in the building lot runoff are mainly in the particulate material. PCBs only originate from atmospheric deposition (Rossi et al., 2004) and background contamination of soils. Thus the increase in PCB concentration can be explained to the background contamination of the eroded suspended solids. For PAH, there might also be a contribution of traffic induced PAH, re-deposited on building and garden surfaces by atmospheric turbulence (the atmospheric collector is situated on a higher building). For NPs, as the production on the building lot concerns both the dissolved and the particulate phase, an emission by the structure of the building is suspected. Indeed, NPs are used in civil engineering industry as admixture in cements and some plastic materials (European Chemicals Bureau, 2002).

Comparison between park outlet concentrations and building entry concentrations reveals a clear decrease for all contaminants, except PAHs which exhibit a surprising increase. Outlet concentrations remain however superior to atmospheric fallout concentration for all contaminants. Particles issued from erosion of gardens and deposits are likely to settle during the transfer in the retention basin, where the flow velocity decreases. Thus the observed reduction of SS and TOC is quite expected. Yet, settling is not the only process involved. The observed reduction of dissolved contaminants proves an adsorption of labile contaminants on substrate or on suspended solids. The behaviour of PAH is more difficult to explain and supposes a local PAH production in the park.

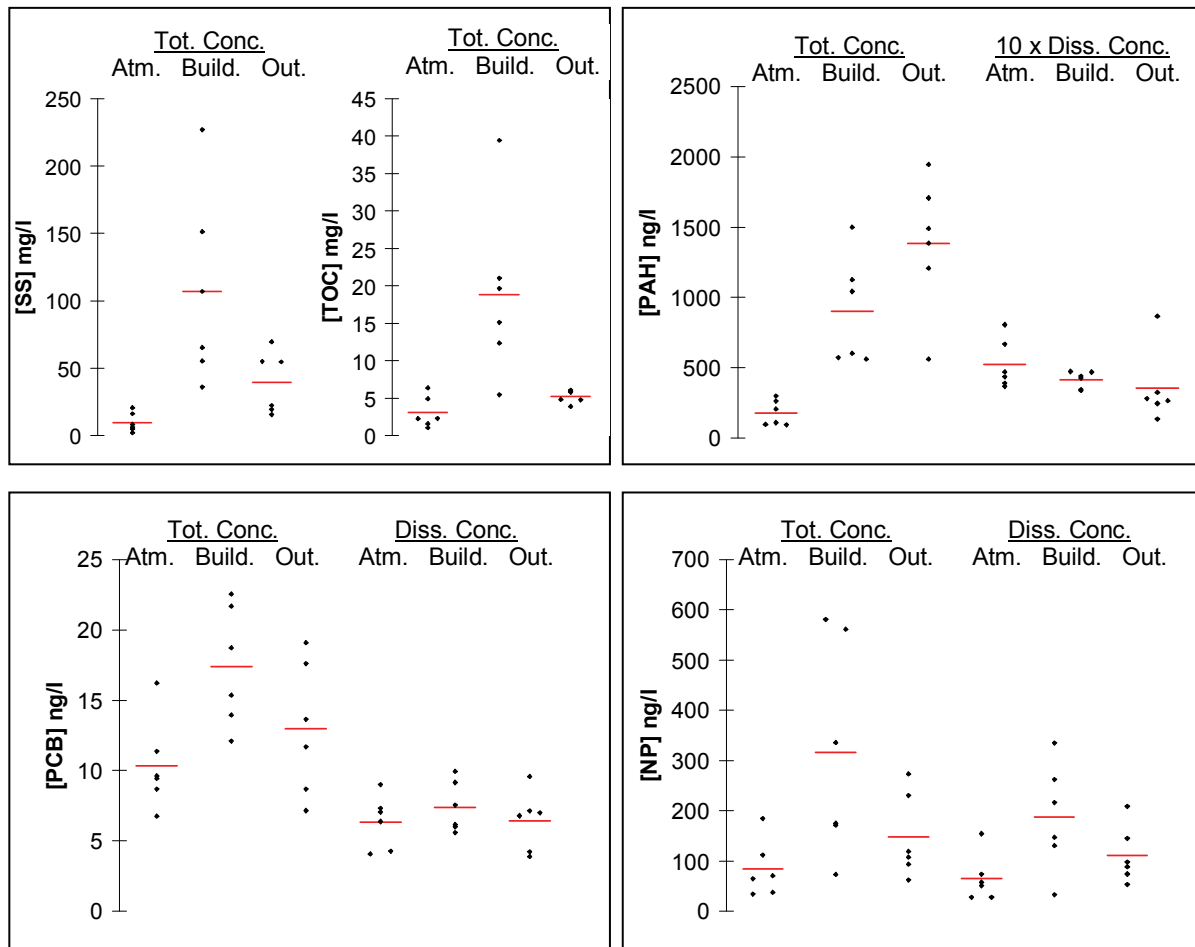


Figure 2: Concentrations (points) and median of concentrations (segments) in total (Tot.) and dissolved (Diss.) fractions for the atmospheric deposition (Atm.), the building runoff (Build.) and at the outlet (Out.)

3.2.2 Mass balances

In order to evaluate the effect of the stormwater retention on the water contamination, entry-exit mass balances were calculated at the watershed scale for the six rain events. Entries were considered to be atmospheric deposition for the play-ground and the paths of the park. Runoff concentrations measured on the experimental building catchment was considered for the 4 building lots. The exit is the emitted mass by the watershed.

The contribution of bulk atmospheric deposition on paths and play-ground was considered to be equal to that measured on the atmospheric collector, and to stream like rain water without any change of concentration. So the mass originating from the paths (M_p) is calculated from the Equation 2, where C_{atm} is the concentration measured in the atmospheric collector.

$$M_p = C_{atm} \cdot H \cdot (RC_p \cdot S_p) \quad \text{Equation 2}$$

The contribution of building releases (M_{build}) was calculated from Equation 3; C_{build} is the concentration in the runoff from the building catchment.

$$M_{build} = C_{build} \cdot H \cdot (S_b + S_g) \quad \text{Equation 3}$$

Results for the comparison of entries and exit are presented in sum of the six events in Table 3.

The transfer and temporary storage of the runoff inside the park has an important effect on the mass of emitted contaminants. Only 26 % of entering PCBs and 18 % of entering NPs are measured at the outlet. For PAHs, the effect is lower but significant; indeed the recovery is around 63 %.

These losses of contaminants are now compared to water losses. PCBs and NPs masses are more

reduced than water volume. An additional depolluting mechanism occurred during water transfer, probably adsorption. Indeed PCBs and NPs are predominantly in the dissolved fraction (54 % for PCBs and 74 % for NPs) and their dissolved fractions are strongly reduced: 22 % of entering dissolved PCBs and 18 % of entering dissolved NPs are measured at the outlet. On the contrary PAHs loss is lower than the water volume reduction even if PAH dissolved fraction (only 2 % of total PAHs) is reduced by 85 %. This result was not expected, because settling should occur during water retention. A hypothesis could be that incoming particles would be settled during retention, but that fine and contaminated by PAHs particles would be released by the garden.

	Water	Total			Dissolved		
		PAHs	PCBs	NPs	PAHs	PCBs	NPs
Entries	521 m ³	306 mg	7 mg	119 mg	36 mg	4 mg	88 mg
Exit	164 m ³	192 mg	2 mg	21 mg	5 mg	1 mg	16 mg
Exit/entries	31 %	63 %	26 %	18 %	15 %	22 %	18 %

Table 3: Entries and exit masses for the sum of the 6 events, and percentages of recovery

3.3 Impacts on garden

The previous paragraph has shown a loss of contaminants between entries and exit that could have an impact on the contamination of garden soil.

3.3.1 Organic micropollutants contents

Organic carbon, PAH, PCB and NP concentrations in soils are summarized in Table 4.

The POC contents of the soil are uniform over the whole storage area: 0.8 % for the 5-15 cm soil layer and 1.4 % for the 0-5 cm soil layer which corresponds to root reach rhizosphere.

PAH contents ranged from 334 to 1146 µg/kg, PCB contents ranged from 26 to 60 µg/kg and NPs contents from 216 to 454 µg/kg of dry material. The measured contents are in line with the literature for this kind of soil. PAH and PCB contents are compared with those measured in soils in the Seine River basin by Motelay-Massei *et al.* (2004). Our lowest contents match the ones measured in remote sites, and our highest match their suburban soil contents (Motelay-Massei *et al.*, 2004). According to the classification of soil contamination established by Maliszewska-Kordibach (1996) (cited by Motelay-Massei *et al.*, 2004), all of the analysed soils are contaminated in PAHs (> 200 µg/kg), or even heavily contaminated (> 1000 µg/kg). The measured PCB contents are in agreement with the suburban soil contents reported by Motelay-Massei *et al.* (2004), are lower than their contents for industrial areas, and higher than their contents for remote sites. NP contents are relatively contaminated compared to Vikelsoe *et al.* (2002). They reported an average value lower than 1 µg/kg in uncultured or conventionally cultured areas, an average value of 34 µg/kg in receiving runoff area, and up to 1000 µg/kg in a sludge amended area. Plants contamination varied between 39 and 338 µg/kg of dry material which is in the same range as those reported by Nadal *et al.* (2004). They measured contents between 28 and 179 µg/kg in chards from unpolluted and residential areas in Spain.

Comparison between the four areas did not show any significant variation according to flood rate for PCBs and NPs. But PAH contents in the two often flooded areas were lower than in the rarely flooded areas with a factor 1.5 to 3 times. So runoff storage seems not to contaminate the garden at least not visibly. The decrease of PAH contents in the frequently flooded areas is surprising and seems to indicate that a depollution process occurs in these areas.

The first 5 cm of soil had the same order of magnitude for PAH and NP contents than the 15 cm below. But they are 1.3 to 2 times lower for PCBs. No infiltration in sub-soil or contamination of the surface by settling and adsorption are highlighted. It has to be noted that the soil of the park is clayey and does not favour infiltration. Perhaps the boundary at 5 cm is too deep to highlight an infiltration effect.

In conclusion, runoff retention in the park seems to not contaminate visibly the soil or the plants. The retained mass of contaminants remains low compared to the initial soil contamination. Different behaviour has been noted for PAHs: PAH contents decreased in often flooded area and are less retained during retention than water volume or other contaminants.

3.3.2 Particles characterization

For better comprehension of organic contaminants fate during retention, characteristics of particles from entries, outlet and garden soil have been compared in Table 4. Contents in particles at the outlet are 33 times higher than in garden for PAHs, 4 times higher for PCBs and 3 times higher for NPs. Emitted particles are therefore not representative of garden particles. But they are neither the same as particles building runoff nor atmospheric deposition. Indeed they are surprisingly contaminated in PAHs: 2 times more than in atmospheric deposition and 3 times more than in building releases. This trend is not observed for POC, PCBs and NPs.

Our hypothesis is that the most contaminated particles in NPs and PCBs would be settled during retention but fine particles, which would be very contaminated in PAHs, would be emitted by the garden soil. That could explain the low PAH contents in the area 1. These fine particles are not stopped by the hydrocarbons separator, which particles contents are lower than at the outlet. But further investigation is needed to validate these hypotheses.

		POC (%)	PAHs ($\mu\text{g}/\text{kg}$)	PCBs ($\mu\text{g}/\text{kg}$)	NPs ($\mu\text{g}/\text{kg}$)
Area 1 often flooded	5 cm	1.5	334	40	454
	15 cm	0.8	334	52	245
Area 2 often flooded	5 cm	1.2	500	26	242
	15 cm	0.5	863	46	294
Area 3 sometimes flooded	5 cm	1.4	1106	35	306
	15 cm	0.8	1146	56	216
Area 4 never flooded	5 cm	1.4	1071	47	318
	15 cm	0.8	918	60	308
HC separator		6.0	3500	92	450
Atmospheric deposition (n=6)		16 \pm 3	13420 \pm 400	673 \pm 194	1870 \pm 1003
Building Releases (n=6)		13 \pm 2	8720 \pm 200	107 \pm 24	940 \pm 461
Outlet (n=6)		4 \pm 2	31130 \pm 1100	182 \pm 22	930 \pm 208

Table 4: Contents in soil from the different areas and median contents in runoff suspended solids

4 CONCLUSION

Our results show that hydrological and quality management of stormwater is improved by detention in a park. The retention allows important runoff volume (68 %) and peak flow reductions comparing to classic separate sewers. As runoff flows are slowed down, decantation of particles and adsorption of dissolved substances increase. This leads to a reduction of the contaminant loads conveyed by stormwaters.

Indeed mass balances at the watershed scale show important retention of contaminants in the garden: only 26 % of entering PCBs, 18 % of entering NPs and 63 % of entering PAHs have been recovered at the outlet. Retention of particles during water storage and adsorption of dissolved substances are suspected. Especially dissolved emitted masses are strongly reduced.

PAHs mass loss is lower than the water volume reduction unlike PCBs and NPs. This behaviour is difficult to explain. Comparison between PAH contents in SS entries, SS from outlet and in garden soil shows that SS from outlet was surprisingly strongly contaminated. A possible explanation could be that incoming particles would be settled during retention, and that fine particles contaminated by PAHs were released by the garden. To validate this hypothesis, it would be interesting to study granulometry of soil and stormwater particles. Moreover sand from playground and materials from street furniture should be analysed to complete the sampling strategy.

The soil analysis has not revealed any soil or plants contamination due to the storage of runoff water. The retained mass of contaminants remains low compared to the initial soil contamination. PAH behaviour is particular. PAH contents decrease in the frequently flooded areas, which could imply that a depollution process occurs in these areas. Further investigation is needed to better understand the complexity of involved phenomena.

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