Conventional settling for the treatment of urban stormwaters in separate sewer systems

Traitement par décantation de la contamination des eaux pluviales séparatives

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ABSTRACT

Stormwater from separate sewer networks in two urban and peri-urban watersheds was analysed to establish the concentrations of contaminants it contains, together with the distribution of dissolved and particulate pollutants. Furthermore, sedimentation of suspended solids (SS) and pollutants in these effluents was assessed by using two protocols currently applied in France: VICAS and VICPOL. Concentrations of SS are higher on Grigny (peri-urban site), whereas trace metal concentrations are lower. The distribution between dissolved phase and particulate phase pollutants follows the same trend on both sites. A non-negligible part of organic contamination and zinc and nickel contamination was found in the dissolved fraction. Median settling velocities measured for SS vary between 0.40 and 0.72 m/h for Tolbiac (urban site) and 0.52 and 1.96 m/h for Grigny (peri-urban site). At the two sites, the settling velocities for contaminants differ significantly from one rain event to another and can be very much lower than those of suspended solids. These results contribute to determine the settling times needed, as a function of the height to which settling basins are filled, to attain statutory objectives in SS reduction.

RÉSUMÉ

Les concentrations en contaminants des eaux pluviales provenant d'un réseau séparatif de deux bassins versants urbain et périurbain, ainsi que la répartition de ces contaminants entre phase dissoute et phase particulaire ont été déterminées. De plus, la décantabilité des matières en suspension (MES) et des polluants de ces effluents, a été évaluée via deux protocoles aujourd'hui utilisés en France : VICAS et VICPOL. Les concentrations en MES sont plus élevées sur le site de Grigny (site péri-urbain), alors que les concentrations en métaux lourds sont plus faibles. En revanche, la répartition des contaminants entre phase dissoute et phase particulaire suit la même tendance sur les deux sites. Une part, non négligeable de la contamination organique et de la contamination en zinc et en nickel, se trouve dans la fraction dissoute. Les vitesses de chute médianes des MES varient entre 0,40 et 0,72 m/h pour le site de Tolbiac (site urbain) et entre 0,52 et 1,96 m/h pour le site de Grigny (site péri-urbain). Sur les deux sites étudiés, les vitesses de chute des contaminants diffèrent de façon importante d'un événement pluvieux à un autre et peuvent être très inférieures à celles des MES. Ces résultats ont permis de déterminer le temps de décantation nécessaire, en fonction de la hauteur de remplissage de l'ouvrage, pour respecter les objectifs réglementaires de traitement sur les MES.

KEYWORDS

Removal of trace metals, Runoff water contamination, Separate sewer network, Settling velocity.

1 INTRODUCTION

Urban stormwater contains mineral and organic contaminants (Choe et al. 2002; Tuccillo 2006; Lamprea and Ruban 2008), in dissolved and particulate form originating from anthropogenic activities. This contamination varies not only from one watershed to another (Stahre and Urbonas, 1990) but also in the same watershed from one rain event to another (Gnecco et al. 2005; Lamprea and Ruban 2008). Most of the contamination occurs in particulate form (Chebbo 1992), consequently, settling proves to be an efficient technique for treating stormwater.

Settling efficiency depends not only on the way settling installations operate, but also on the type of effluent in terms of its dissolved/particulate distribution and the sedimentation velocities of suspended solids and associated pollutants. Evenso research has been carried out on separate stormwater networks (Choe et al. 2002; Ruban et al. 2005), few data exists for characterising sedimentation in this type of water (Daligault et al. 1998; Aires et al. 2003). The aim of this article is to provide information on the theoretical efficiency of treating urban stormwater in a separate sewage network by using a simple settling process.

2 MATERIALS & METHOD

2.1 Description of sites and the method of sampling

Samples were taken from two sites. The first, known as the Tolbiac site, with a surface of 64 ha is located in the city of Paris (75). It is characterised by a dense urban-type land-use. The second site is at Grigny, located in the south of Paris-conurbation. This peri-urban watershed has a surface area of 430 ha (Table 1).

Site		Tolbiac	Grigny
Watershed			
Surface (ha)		64	430
Imperviousness coefficient (C_{imp})		0,8	0,4
Maximal steepness (%)		0,7	3,5
Land use	Enterprise parks/offices/equipment	69%	17%
	Transport infrastructures	1%	16%
	Natural and agricultural areas	2%	22%
	Individual housing	0%	32%
	Apartment blocks	26%	12%
	Worksites	2%	1%
Monitoring conditions			
Number of sampled rainfall events		5	6
Precipitate heights (mm)		6-27	4-32
Maximum intensities over 15 minutes (mm/h)		11-36	3-78
Length of dry period prior to the event (d)		0-21	4-22

Table 1: Characteristics of the two sites under study and the rainfalls sampled

These watersheds are both drained by a separate sewage network with a downstream on-line settling tank for stormwater treatment.On the Tolbiac site, the water is discharged into the river Seine after treatment. Its quality is subject to a regulatory ruling on the discharge of stormwater into the river Seine dated 24 December 1999, that sets, for stormwater below the basin’s maximum storage capacity, a maximum concentration of 40 mg/l for suspended solids, 90 mg/l for COD (chemical oxygen demand), and 5 mg/l for hydrocarbons (instantaneous maximum). On the Grigny site, water is discharged into Lake Arbalète after treatment. Water treatment plant performances comply with the requirements stipulated in the discharge permit issued by the prefectoral offices in conformity with water law stipulations. Consequently, the settling tank was designed for an annual yield of 80 % on suspended solids, for a per-event yield of 60 % on suspended solids and for a residual concentration of 5 mg/l in floating hydrocarbons. Both settling tanks have been sized for the removal of SS with settling velocities higher than 1 m/h.

Five rainfall events were investigated on the Tolbiac site between May and August 2008 and six on the Grigny site between October 2008 and July 2009 (Table 1). Stormwater was sampled from the separate sewage networks on these watersheds using automatic samplers.

2.2 Physicochemical analyses and analyses of settling velocities for particles and contaminants

Time proportional samples were collected at the inlet of the detention tanks. Each sample was analysed in terms of suspended solids, COD (chemical oxygen demand), POC (particulate organic carbon) and metals (Lead, Zinc, Cadmium, Nickel, Copper). Effluent sedimentation was characterised by establishing the settling velocities of suspended solids together with those of COD, POC and trace metals by using two protocols: VICAS and VICPOL (Gromaire et al. 2007, Chebbo and Gromaire 2009). In France, these protocols are recognised as reference protocols for establishing settling velocities of urban wet weather flows and therefore enable comparisons with other sites.

3 RESULTS AND DISCUSSION

3.1 Concentrations in stormwaters from separate sewage networks

The concentrations of suspended solids observed on both sites are different (Table 2). They vary from 66 to 212 mg/l for the Tolbiac site and from 83 and 850 mg/l for Grigny. Moreover, these concentrations vary significantly from one event to the next on the same site. Therefore, the stormwater's physicochemical characteristics do not only depend on watershed characteristics but also on rain event characteristics.

Parameters	Tolbiac	Grigny	(Ruban et al. 2005; Lamprea and Ruban 2008)*	(Gromaire et al., 2001)	(Zgheib, 2009)	(Tuccillo, 2006)
Suspended solids (mg/l)	66-212 (167)	83-850 (241)	42-366 (141) ***(112)***	30-75 (36)	58-430 *(193)*	--
COD (mg/l)	41-277 (77)	64-157 (132)	***(31)***	43-113 (56)	48-230 *(125)*	--
POC (mg/l)	7-28 (11)	18-45 (24)	--	--	--	--
Pb (µg/l)	36-43 (37)	8-56 (16)	5-52 (16) ***(21)***	257-724 (425)	62	5-38 ***(15)***
Zn (µg/l)	237-473 (394)	130-287 (170)	39-405 (128) ***(183)***	2 297-8 877 (3199)	280	8-201 ***(67)***
Cd (µg/l)	<1	0,1-0,4 (0,2)	<0,1-2 (0.2) ***(0.4)***	1,4-4,1 (1,8)	<2	--
Ni (µg/l)	--	8-41 (33)	<2-27 (7) ***(8)***	--	<20	--
Cu (µg/l)	56-61 (58)	32-100 (38)	2-89 (20) ***(28)***	37-131 (56)	105	3-65 ***(17)***
Site characteristics			Two discharges from separate peri-urban networks C_{imp}=0,5 and 0,3	Runoff water Dense urban site C_{imp}=0,9	Discharge from separate peri-urban network C_{imp}=0,6	Six discharges from separate peri-urban networks (C_{imp}=0,2 and 0,6) and roads

--: Non-established

(x), ***(x)***: *Median value, average value*

**: Median values according to Lamprea and Ruban (2008) and average value according to Ruban et al. (2005)*

Table 2: Ranges and median values in brackets of contaminants contained in stormwater

Suspended solid concentrations are higher on the Grigny peri-urban site, but still remain lower than those highlighted (490 mg/l in median value) by Aires et al. (2003) on a peri-urban watershed in the Paris area. On the one hand, the high concentrations observed on the Grigny site are linked to the fact that the streets are not cleaned frequently and, on the other, to the size of the erodible surfaces that lie on a steep slope. Concentrations in suspended solids brought to light on the Tolbiac site correspond to those observed on several other separate networks (Lamprea and Ruban, 2008; Ruban et al., 2005 ; Zgheib, 2009) but are considerably less significant than those observed by Gromaire et al. (2001) in runoff water in the “Marais” neighbourhood in central Paris. On the other hand, concentrations in suspended solids observed on the Grigny site correspond to those discovered by Choe et al. (2002) on the discharge from urban watersheds in Rep. of Korea.

Concentrations of metallic micro-pollutants observed on the dense urban site of Tolbiac are higher than those observed on the peri-urban site at Grigny. The median concentration in lead is 37 µg/l on the Tolbiac site and 17 µg/l on the Grigny site, that of copper reaches 58 µg/l for Tolbiac and 38 µg/l for Grigny, and, lastly, the median concentration in zinc is 394 µg/l for Tolbiac and 170 µg/l for Grigny. These results may be explained by the higher levels of urbanisation on the Tolbiac site. However, lead, zinc and cadmium concentrations remain significantly lower than those observed in runoff water in an older neighbourhood of Paris, where buildings have old zinc roofs and lead water-proofing elements, both of which contribute considerably to the amount of trace metals found (Gromaire et al., 2001). These concentrations are also lower than those observed by Choe et al. (2002) in the discharges from urban watersheds where impervious surfaces are not often cleaned. Lastly, concentrations in zinc and copper are higher than those reported by Tucillo (2006) in discharges from peri-urban and roadway watersheds in Genoa (Italy).

3.2 The distribution of contamination between dissolved and particulate phases

Over 72 % of the lead found in runoff water on the Grigny and Tolbiac sites is found in particle form (Table 3) as has already been observed in runoff water in other urban and peri-urban environments (Chebbo, 1992; Cheng, 1994; Gromaire-Mertz et al., 1999; Ruban et al., 2005; Zgheib, 2009). To a lesser extent, most copper pollution is also adsorbed by particles. As a result, a median value of 82 % of the copper is in particulate form on the Tolbiac site and 78% on the Grigny site. On the other hand, a non-negligible part of contamination by nickel (45 % at Grigny in median value) and by zinc (47 % at Tolbiac and 36 % at Grigny in median values) is in dissolved form, a phenomenon also clearly shown by Ruban et al. (2005) for a peri-urban watershed. Similarly, 49 % and 33 % of the COD found at Tolbiac and Grigny respectively is in dissolved form. Consequently, the efficiency of settling treatment on these contaminants is limited.

	Tolbiac	Grigny	(Ruban et al., 2005)	(Zgheib, 2009)
Pb	> 72*	76-100 (95)	***(90)***	~100
Cd	--	> 68*	***(70)***	61-69
Cu	63-85 (82)	56-94 (78)	***(70)***	66-88
Zn	45-76 (53)	48-87 (64)	***(47)***	54-98
Ni	--	27-78 (55)	***(40)***	69-79
COD	50-76 (51)	43-87 (67)	--	--

--: Non-established
(x), ***(x)***: *Median value, average value*
**: Dissolved fraction non-detected*

Table 3: Minimum and maximum values and median values in brackets of contaminants in particle form in percentage

The distribution between dissolved and particulate phases is similar on both sites and trace metals have similar affinities with suspended solids. Therefore, the dissolved-particulate distribution appears to depend very little on land use, as has already been observed by Zgheib (2009).

Trace metal and organic pollutant contents in the particulate phase are higher on the dense urban site at Tolbiac than on the peri-urban site at Grigny (Table 4). The median content in copper is 448 µg/g dry weights on the Tolbiac site, but only 274 µg/g dry weights at Grigny. Similarly, the zinc content is 1336 µg/g dry weights for Tolbiac and 815 µg/g dry weights for Grigny. This is linked with the fact that runoff water on the Tolbiac site contains less suspended solids and more trace metals, due to denser land use on this watershed. Median values observed on the Grigny site are also much lower than those observed by Zgheib (2009) on two peri-urban sites in the Paris area (Table 4).

	Tolbiac	Grigny	(Zgheib, 2009)#
Pb (µg/g dw)	>123*	13-185 (121)	(217) – (279)
Cu (µg/g dw)	235-452 (448)	30-340 (274)	(500) – (550)
Zn (µg/g dw)	865-1 726 (1336)	101-1 558 (815)	(2 562) – (1 697)
Ni (µg/g dw)	--	13-337 (47)	--
COD (mg O_2/g dw)	240-1642 (495)	33-845 (456)	--
POC (mg C/g dw)	52-168 (78)	21-134 (30)	--

--: Non-established
#: (x) – (y): Median values on two peri-urban sites
**: Dissolved fraction non-detected*

Table 4: Ranges and median values in brackets for particle content in contaminants

3.3 Sedimentation of suspended solids and contaminants

Establishing settling velocities for suspended solids has enabled curves to be drawn (Chebbo and Gromaire, 2009), indicating the cumulated percentage of the gross weight of particles with a settling velocity lower than Vc (Figure 1).

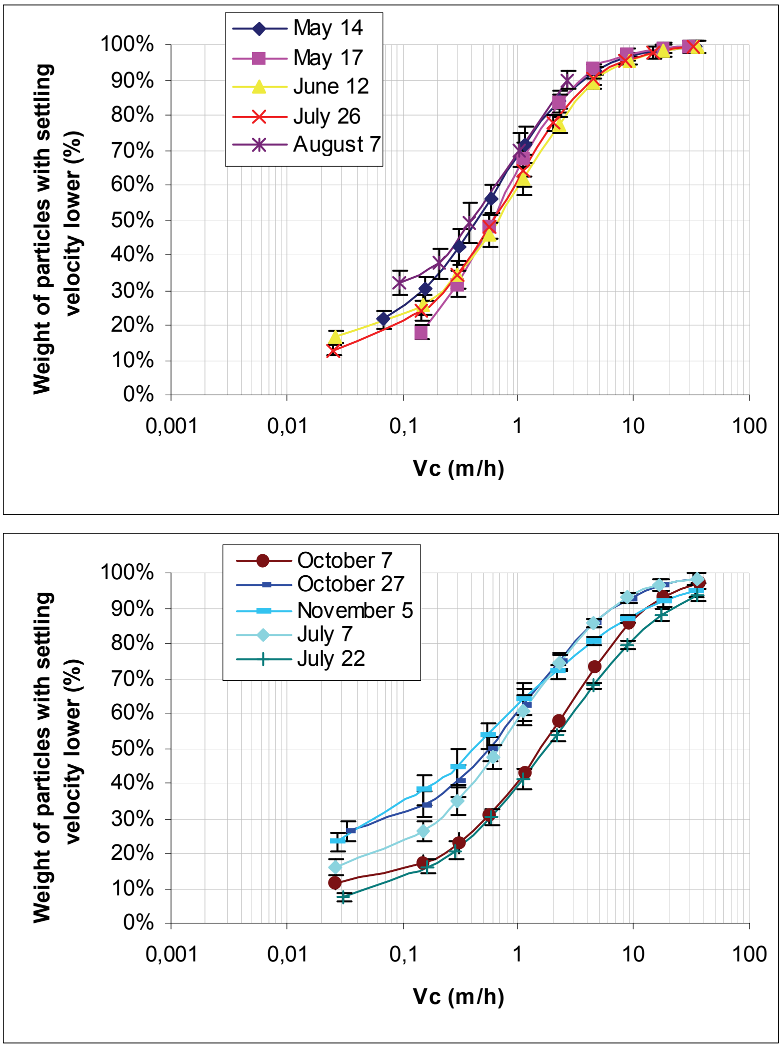

Figure 1: Settling velocity curves (m/h) for suspended solids on the Tolbiac (top) and Grigny (bottom) sites

Settling velocities vary from one site to another and from one rainfall to another on the same site (Figure 2). The median settling velocity (V50) varies from 0.40 m/h to 0.72 m/h for the Tolbiac site, whereas it varies from 0.54 m/h to 1.96 m/h for the Grigny site (Table 5). Values measured at the Grigny site are similar in size to those observed by Aires et al. (2003) on a peri-urban watershed with equivalent urbanization in the Paris region, whilst values measured at Tolbiac correspond more to those observed by Daligault et al. (1998) on two peri-urban watersheds with similar land use in the Paris region. Settling velocities enabling 80 % of SS to decant (V20) are less than 0.17 m/h for the Tolbiac site whereas they are less than 0.30 m/h for the Grigny site.

Inter-event variability is much higher at Grigny. This can be explained by the specificity of the watershed : pervious areas and the steep slope contribute to soil erosion during intense rainfall events. Furthermore, settling velocities are higher. On the one hand, this difference may be due to the high concentrations of suspended solids on the site that contribute to creating flocs with high settling velocities (Randall et al., 1982). On the other hand, the steep slope on the watershed favours the carry-over of particles with high settling velocities.

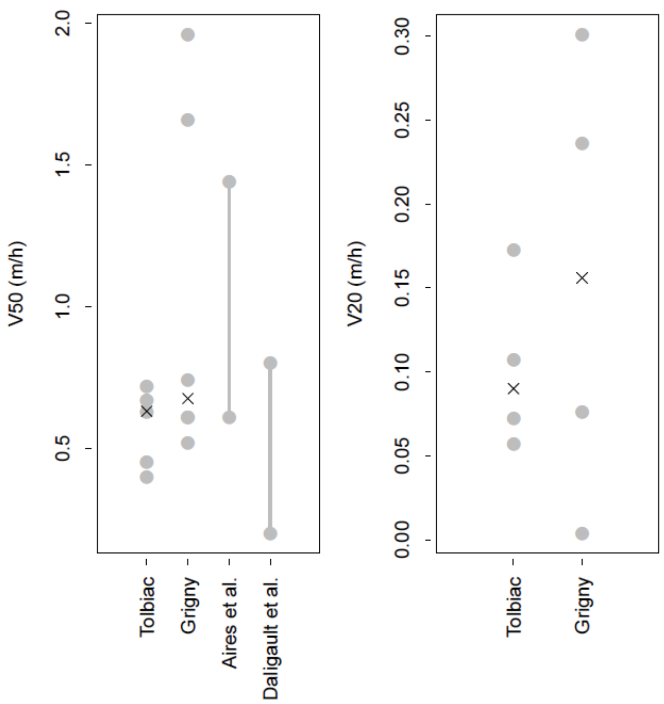

Figure 2 : Median settling velocities (V50) and settling velocities enabling 80 % of SS to decant (V20) on Tolbiac and Grigny sites. Points indicate values of settling velocities for each rainfall event sampled. Crosses indicate median values.

Median settling velocities (V50) for trace metals vary from 0.25 to 0.72 m/h for the Tolbiac site and from 0.08 to 1.84 m/h for Grigny. Settling velocities for organic contaminants vary from 0.08 to 0.72 m/h for the Tolbiac site and from 0.05 to 2.23 m/h for Grigny (Table 5). As seen for suspended solids, settling velocities for contaminants tend to be higher and much more variable from one rain event to another on the Grigny site.

	Tolbiac		Grigny	
	Number of events	V50 (m/h)	Number of events	V50 (m/h)
COD	5	0.08-0.72 (0.28)	4	0.05-2.23 (0.56)
POC	4	0.23-0.54 (0.45)	2	0.10-1.48
Pb	--	*	3	0.10-1.19 (0.54)
Zn	4	0.25-0.72 (0.51)	3	0.08-1.26 (0.11)
Cu	2	0.32-0.54	4	0.10-1.44 (0.61)
Ni	--	--	4	0.36-1.84 (0.72)

--: Non-established
**: Dissolved fraction non-detected*

Table 5: Range of median settling velocities (V50) and median values in brackets of particulate contaminants

Contaminant settling velocities may differ from those of suspended solids. Moreover, the behaviour of these settling velocities varies considerably from one rainfall to another. Therefore, reasoning purely in terms of suspended solids may prevent certain contaminants from being treated efficiently. For example, on both sites organic contaminants have settling velocities lower than for suspended solids in the case of four rainfalls out of nine for COD and six rainfalls out of seven for POC.

Settling velocity measurements for both suspended solids and contaminants made it possible to assess the treatment yield that would be reached for different contaminants when an SS treatment yield of 60 % is reached (Table 6). Moreover, the corresponding output concentration was also estimated. A treatment facility sizing approach that would be based only on SS settling velocities, may lead to poor efficiencies regarding the treatment of the associated contaminants. For instance, the treatment yield for particle-bound organic matter can fall to values below 40 % for some rain events. Moreover, if we consider total COD (including the dissolved fraction), the median treatment value drops to 31 % on the Tolbiac site and to 42 % at Grigny. Similarly although settling treatment permits reaching median values close to 60 % for particulate copper and zinc, efficiency drops to 42 % for total copper and 32 % for total zinc on the Tolbiac site (respectively 51 % for total copper and 44 % for total zinc at the Grigny site), when taking also the dissolved fraction into consideration. Median particulate efficiency for lead is 55 % at Tolbiac and 49 % at Grigny. This efficiency varies little when taking into account the dissolved fraction as most of the lead is attached to particles. On the other hand, the median efficiency for nickel, which is hardly adsorbed by particles, is relatively low if the dissolved fraction is taken into account (32 %).

	Tolbiac			Grigny		
	Efficiency on particulates (%)	Efficiency on total (%)	Residual concentration (mg/l)	Efficiency on particulates (%)	Efficiency on total (%)	Residual concentration (mg/l)
COD	38-64 (60)	19-50 (31)	29-224 (43)	30-72 (60)	12-62 (42)	38-127 (75)
POC	22-58 (57)	--	--	51-64 (58)	--	--
Cu	45-57 (58)	35-53 (42)	26-68 (45)	55-68 (61)	41-55 (51)	17-48 (29)
Zn	60-70 (60)	28-54 (32)	109-323 (276)	44-61 (51)	29-50 (44)	99-143 (101)
Pb	42-62 (55)	39-55 (47)	16-23 (21)	30-71 (49)	30-55 (47)	6-34 (11)
Ni	--	--	--	41-83 (71)	15-59 (32)	3-34 (19)

--: Non-established

Table 6: Ranges of efficiency and median values for contaminants and the residual concentration corresponding to works sized for settling 60% of suspended solids

Simulated median event-mean output concentrations for lead, after settling giving a 60 % reduction in suspended solids, are 21 µg/l on the Tolbiac site and 11 µg/l at Grigny. These concentrations are higher than the environmental quality standard (Directive n°2008/105/EC), which sets an annual average concentration of 7.2 µg/l. Similarly, environmental quality standards set an average annual concentration of 20 µg/l for nickel, which is exceeded two times out of four at the Grigny site.

3.4 How much settling time is needed to comply with discharge permits?

Settling efficiency simulations were performed using Tolbiac and Grigny's data set with the following assumptions :

- Simple settling tank without lamella and coagulation process
- No throughflow
- Settling height equal to maximum water depth measured in real tank for the considered rain event
- Still water settling conditions
- Homogeneous concentration at the beginning of the settling process and equal to the mean entry concentration
- Treatment objectives taken into account are those of statutory objectives

Statutory objectives for Tolbiac runoff water treatment plant are 40 mg/l for suspended solids. These objectives were converted into a treatment yield for each rainfall. The per-event treatment yield on suspended solids required for the Grigny detention tank is 60 %.

Suspended solid concentrations during settling were simulated on the basis of the settling velocities measured for each event and by hypothesising that settling in water treatment plants resembles settling in a column of still water. This enabled us to establish the settling time needed to attain the required treatment yield. For a given rainfall, the settling time varies linearly according to the height to which the basin is filled. Relationships have been assessed that link the storage height in the basin to the settling time needed (Table 7). These relationships vary depending on the characteristics of the stormwater (concentrations of suspended solids and particle settling velocities).

Data set	Date of rainfall	Target output SS concentration (mg/l)	Corresponding treatment yield	Relationship between time and height of settling	Theoretical settling time needed
Tolbiac	May 14	40	84%	t=16.46.h	3h17
	May 17	40	77%	t=2.39.h	58min
	June 12	40	79%	t=5.81.h	2h55
	July 26	40	61%	t=1.10.h	2h05
		Target treatment yield	Corresponding output SS concentration (mg/l)	Relationship between time and height of settling	Theoretical settling time needed
Grigny	October 7	60%	58	t=0.44.h	2h28
	October 27	60%	317	t=1.56.h	9h52
	November 5	60%	340	t=1.81.h	10h19
	July 7	60%	40	t=1.04.h	5h56
	July 22	60%	135	t=0.37.h	2h20

Table 7: Straight-line equations relating settling time (t in hours) to the height to which basins are filled (h in metres) for every rain event

The settling time needed to comply with statutory objectives varies from 58 minutes to 3h17 for the Tolbiac site and from 2h20 to 10h19 for Grigny. Settling time is high on the Grigny site due to the storage height. Storage levels are at around 6 m whereas they are from 20 cm to 2 m for the Tolbiac site. Settling time variability is very considerable for Grigny, which increases difficulties in terms of managing the sedimentation tank. The use of a continuous measurement system, e.g. turbidity, would enable adapting the detention time to each rainfall. These theoretical calculations of settling times must however be interpreted with care and need to be validated by on-site measurements.

Output concentrations may be high if objectives are limited merely to the treatment yield. As a result, on the Grigny site, concentrations of suspended solids in the water after treatment can attain levels of up to 300 mg/l for two rain events with considerable input loads. Conversely, the objective of 40 mg/l for suspended solids set for Tolbiac would appear to be relatively ambitious and corresponds to high treatment yields (from 61 % to 84 %).

4 CONCLUSION

The objectives of this work were to characterize the pollutant loads (SS, COD, POC and metals) of separate stormwaters from urban and peri-urban watersheds, and to estimate their settling ability by analysing settling velocities for both particles and contaminants.

Physicochemical analyses show concentrations of suspended solids that are much higher for the Grigny peri-urban watershed than those observed for the dense urban watershed at Tolbiac. This difference is probably related, on the one hand, to land use and local practises (street cleaning), and to the topography of the sites on the other. Concentrations in metallic micro-pollutants are higher on the Tolbiac site due to the higher density of buildings.

Settling velocities for suspended solids not only vary from one site to the other, but also on the same site from one rainfall to another. They are higher and vary more on the Grigny site. This difference may be explained by the high concentrations of suspended solids as well as by the steep slopes that characterise this watershed. The settling velocities of suspended solids shown in this work are lower than those usually used for sizing settling basins. Furthermore, the settling velocities of contaminants differ from those of suspended solids. These settling velocities should also be taken into consideration if organic and mineral pollution must also be treated.

The theoretical settling time required to comply with statutory discharge objectives for suspended solids and for both sites was assessed. It varies from 58 minutes to 3h17 for the Tolbiac site and from 2h20 to 10h19 for Grigny, depending on the rain event studied. Even though particles have higher settling velocities on the Grigny site, the settling times needed to comply with statutory objectives are higher. This is related to the high levels of storage in the settling basin. Settling times also vary depending on the rain event. Permanent measurement of suspended solids would allow validating the representativeness of these theoretical calculations in relation to what actually occurs in the basin and to adapt settling time to each rainfall. For certain rain events with heavily loaded inputs, statutory treatment yield objectives may lead to high concentrations in suspended solids still remaining after settling. These concentrations raise even more problems, when the water is discharged into a closed environment, which is the case for the Grigny site.

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